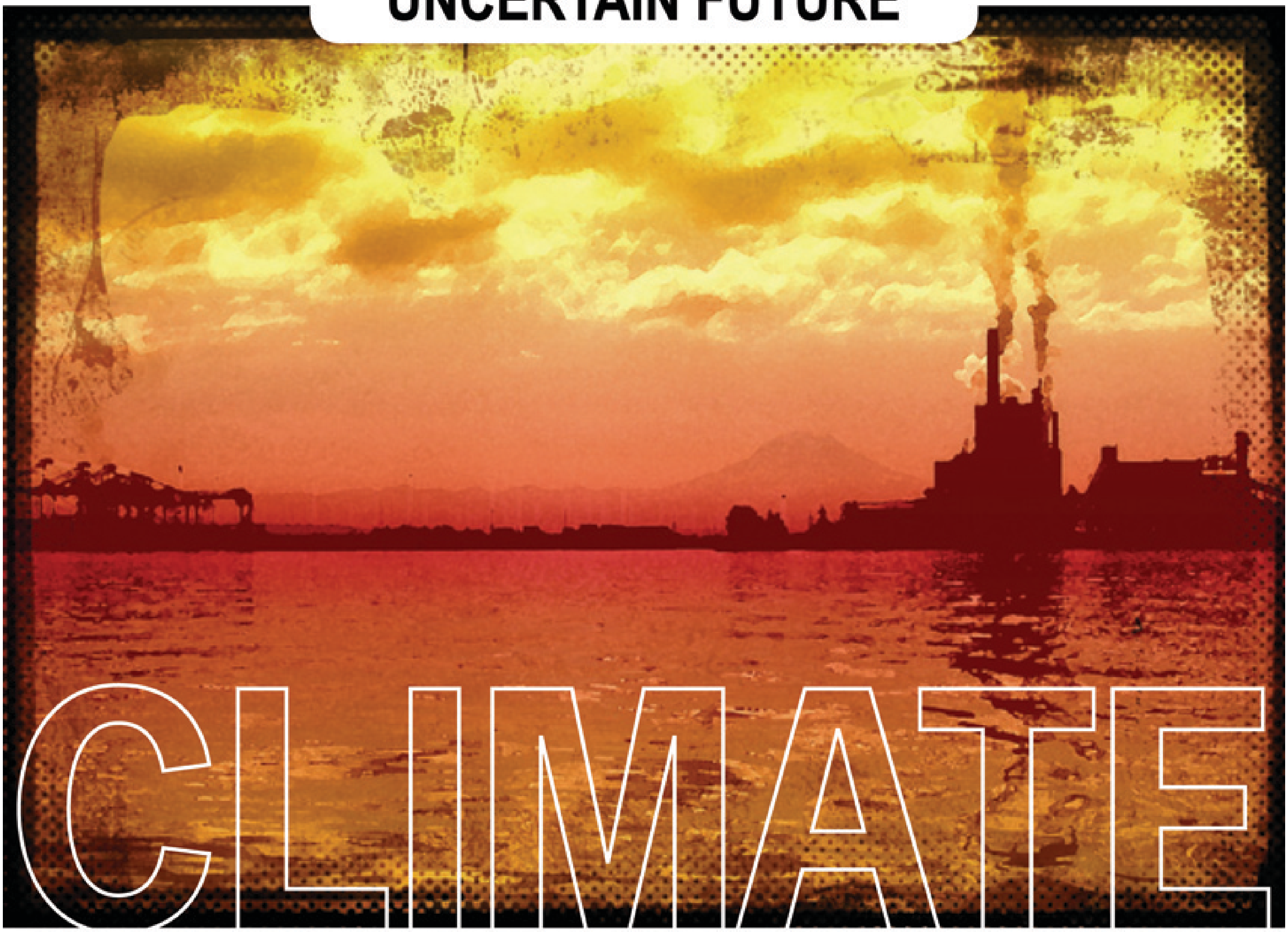
UNCERTAIN FUTURE



CLIMATE

CLIMATE CHANGE AND ITS EFFECTS ON PUGET SOUND

FOUNDATION DOCUMENT

The Climate Impacts Group, University of Washington

commissioned by

PUGET SOUND ACTION TEAM

Office of the Governor | State of Washington

October 2005

A report prepared for the Puget Sound Action Team

by

the Climate Impacts Group
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For copies of this report or the shorter overview document, both in portable document format (pdf) see cses.washington.edu/db/pubs/abstract460.shtml or www.psat.wa.gov/climatechange/

Foreward

The Puget Sound Action Team coordinates protection and restoration of Puget Sound. Over the years the Action Team's work has focused predominantly on remedying the legacies of the past and mitigating the immediate impacts of current activities. Yet, it is also our duty to anticipate future threats to the health of the Sound. We commissioned this work by the University of Washington's Climate Impacts group so that we might begin to better understand the implications of global warming for Puget Sound.

After looking at the evidence, I am personally deeply worried about the threats to Puget Sound and our society posed by a rapidly changing climate. We are already seeing significant changes in our climate, including warming temperatures, diminished snowpack and rising sea levels. Combined with other impacts you will read about in this report, these changes pose a significant threat to the fundamental natural infrastructure upon which our region has developed and our environment has depended.

This report will help us to insert the reality of climate change impacts into the mix of environmental and development management decisions in the Puget Sound basin. We must continue to improve our knowledge of the potential impacts. At the same time, all of us with management responsibilities in the basin need to adapt our management actions to account for and accommodate the projected changes as best we can.

To ignore what the science is telling us about climate change would be irresponsible. Adaptation to a changing climate is an imperative. I hope that this report will help all of us in that important work.

Sincerely,

Brad Ack
Director
Puget Sound Action Team

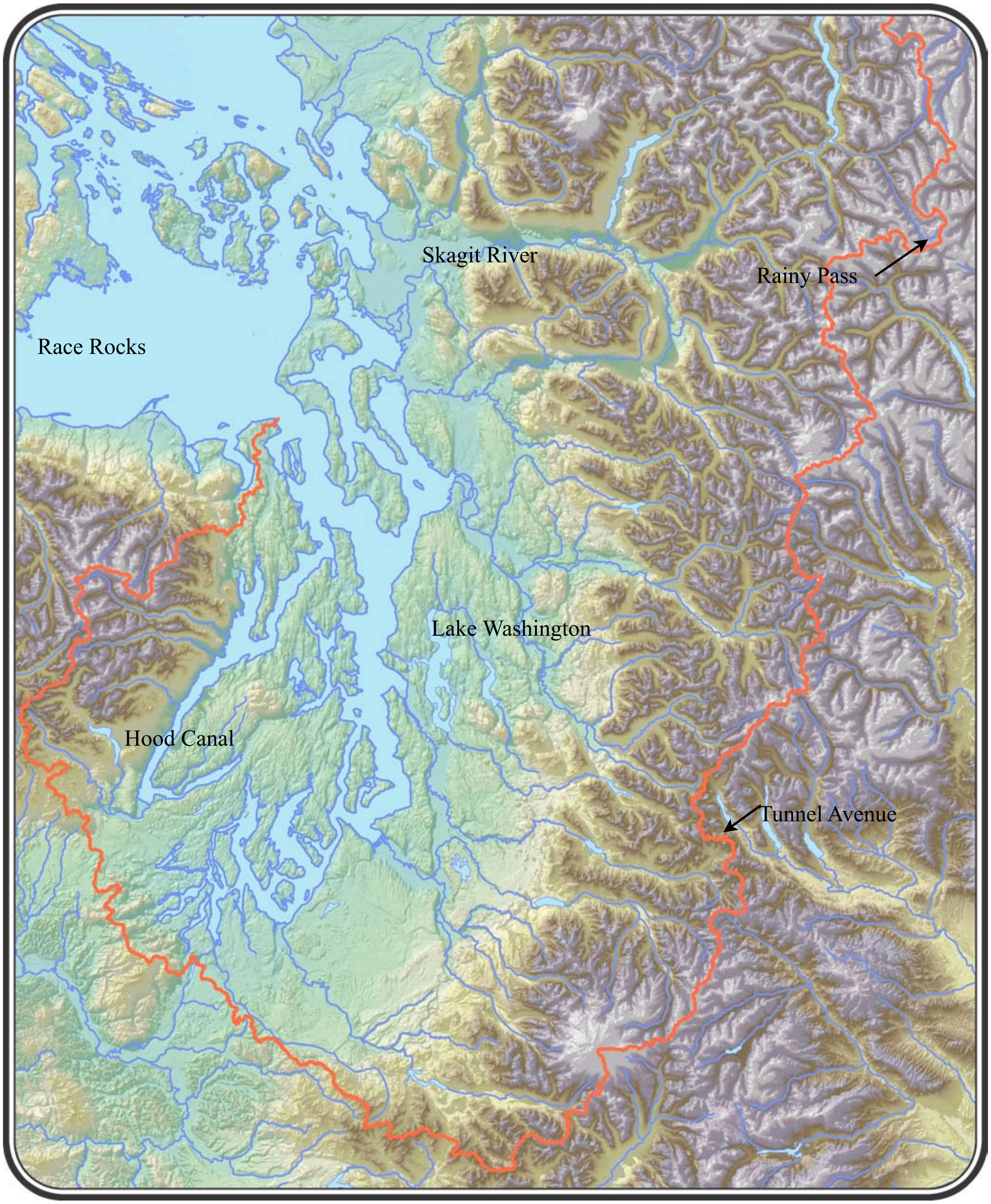

Figure 1. Map of Puget Sound watershed (outlined in red) with key features labeled.

1 Introduction

In the Puget Sound region (Figure 1), beautifully intertwined marine and terrestrial environments create rich ecological diversity. This landscape and seascape support orcas and eagles, salmon and foxes, mice and minnows. The shores of the Sound are lined with forests, farms, commercial shellfish beds, Indian reservations, urban landscapes, military installations, wetlands, bluffs and beaches. Economic and aesthetic values of these natural resources – and, not least, the recreational benefits offered by the proximity of mountains and water – have attracted new residents at such a rate that population growth has been more than double the national average for each of the past 50 years[1].

Rapidly growing human demands on the terrestrial and aquatic resources have, of course, compromised the integrity and functioning of the environment. Some of the changes are obvious to the layman: forests and concrete, for example. More than 90% of the region's old growth forest has been logged, mostly replaced by commercial timber plantations (which often contain but a single species of tree) and also by urban areas and farms. Almost all of the major streams that flow into the Sound have been dammed: the Skagit, which produces hydropower for the city of Seattle; the Green/Duwamish, Cedar, and Sultan, which provide water for the cities of Tacoma, Seattle, and Everett; even the Nisqually and White Rivers, which flow from the flanks of Mount Rainier, and the very short Skokomish River on the Olympic Peninsula, are dammed. Two of the biggest rivers, the Skykomish and Snoqualmie, are uninterrupted by concrete on their main stems, but have tributaries that are dammed. Much of the shoreline in urban areas has either been built over or hardened with concrete or riprap (piles of large rocks).

Some of the changes have been subtler and most residents may be unaware of the changes. The flux of human commercial and botanical activity has also introduced numerous nonnative species that have spread rapidly: Himalayan blackberries, Scots broom, and English ivy on land, and in the coastal waters of Washington (but not yet, fortunately, Puget Sound) European green crab *Carcinus maenas* and the marine weed *Spartina*[2]. Other, indigenous species have declined, like spring chinook salmon and orcas.

Subtler still are the changes that can be detected only with careful measurement and analysis. During the past 150 years, human activity on a global scale has changed the composition of Earth's atmosphere in important ways: Carbon dioxide, at 379 parts per million (ppmv), is 32% more abundant than it was for thousands of years before the industrial revolution (Figure 2), and has reached values unprecedented in probably the past 20 million years[3]. The second most-important greenhouse gas, methane, has risen 151% above preindustrial values, many others like nitrous oxide have increased, and some entirely man-made compounds (e.g., the chlorofluorocarbons) are also found at climatically significant levels[4].

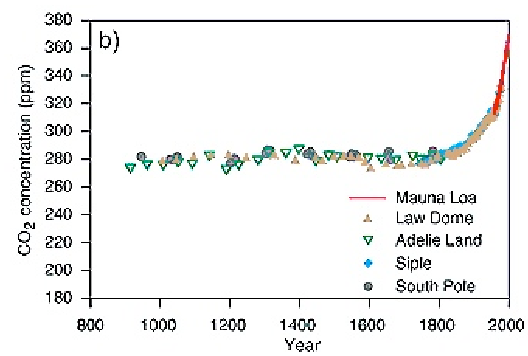

Figure 2. Carbon dioxide observed in Antarctic ice cores (colored symbols) and directly since 1956 (red). Source: IPCC, 2001.

[1] Mote et al. 1999

[2] King County Natural Resources Department, dnr.metrokc.gov/wlr/waterres/marine/exotic.htm

[3] Prentice et al. 2001.

[4] Prather et al. 2001.

These gases, though comprising in total less than 0.04% of the atmosphere, matter greatly because they absorb infrared energy, thereby keeping Earth warm: they are the “greenhouse gases.” Thanks to their absorption and emission of infrared energy, these gases enable the atmosphere to contribute, on average, 324 W/m^2 of energy to Earth’s surface, whereas solar energy only contributes on average 168 W/m^2 (ref. 5). During the past ~700,000 years, Earth has experienced 7 glacial-interglacial cycles, in which global temperature changes by 5-8°C and carbon dioxide changes from ~180 to ~280 ppmv[6]. These cycles brought massive changes, including large-scale changes to the Earth’s physical appearance, such as ice sheets over Puget Sound, and reorganizing of diverse ecosystems. If an increase of 50% in CO_2 is associated with the difference between an ice age and an interglacial, we should expect some response of surface temperature to the observed increase in greenhouse gases. The question is whether such changes have been observed. This question is taken up in Section 2.

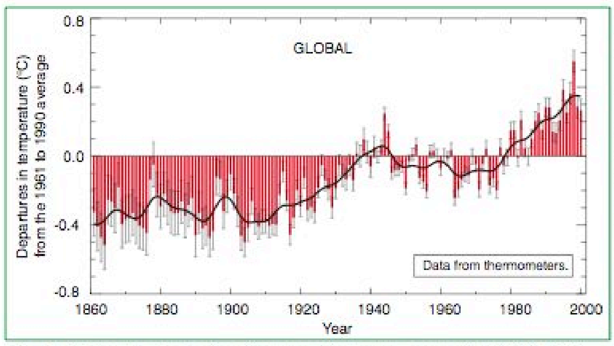

Figure 3. Annual global average temperature anomalies relative to the 1961-90 mean. Two standard error uncertainties are shown as bars on the annual number, and a smoothed curve (black) is also shown.

Discerning the consequences of past climatic change (chiefly in the past 100 yr) in the Puget Sound region, and deducing the consequences of the much larger future change, are the subjects of this report. We distinguish between climate variability, which are the year-to-year and decade-to-decade fluctuations, and climate change, that is, changes over periods of 30 yr or longer.[7] This document describes studies pertinent to environmental changes in the waters of Puget Sound, and draws on studies of connections between climate and biological indicators to infer some possible future changes in freshwater and marine ecosystems.

2 Changes in climate

2.1 Global changes in climate

As noted in the introduction, simple physics dictates, and geological history shows, that increasing greenhouse gases in the atmosphere leads to an increase in air temperature at the surface of the earth. Indeed, during the 20th century Earth’s average surface air temperature rose about 0.6°C±0.2°C (1.1°F ±0.4°F) (Figure 3)[8], a rate that is probably unprecedented in at least the past 1000 years[9]. A considerable body of research leads to the conclusion that the increase in globally averaged temperature in the past 30-50 years is largely due to the rapidly rising greenhouse gases[10]. One line of evidence supporting this conclusion is the growing similarity between the pattern of observed temperature trends and the pattern predicted by global climate models (see section 2.3) with enhanced greenhouse gases. Another line of evidence is that natural agents of climate forcing,

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[5] Kiehl and Trenberth 1997.

[6] Prentice et al. 2001.

[7] Using several statistical techniques collectively called “attribution”, which seeks to ascribe observed changes in climate to external causes like greenhouse gases or solar activity, researchers have determined that greenhouse gases have almost certainly contributed to the warming of the 20th century, on scales from 1000 miles or so to global. However, attribution is not yet possible at the scale of Puget Sound: hence, any changes we describe in this document cannot unequivocally be attributed to human influence on global climate.

[8] Folland et al. 2001, and references therein.

[9] Mann et al. 2003, von Storch et al. 2004 and Moberg et al. 2005.

[10] Mitchell et al., 2001, and refs. therein

namely volcanic eruptions and solar fluctuations, would have produced a cooling over the last 50 years.

Concentrations of greenhouse gases are much higher than they have been at any time since the rise of civilization 10,000 years ago. The climate, land surface, glaciers, and oceans are responding to these changes with some delays as noted above. Anticipating future directions of change are crucial if we intend to minimize the impacts of future change.

2.2 20th century climate change in the Puget Sound Region

Although systematic weather records date back to the 19th century in the Puget Sound region, these records generally cannot be used unmodified for quantifying long-term changes in climate. For example, changes in thermometer, observing time, or location can result in changes exceeding 1°C, often larger than the true climate trend over a time scale of many decades. Climate-quality records can, however, be reconstructed from these weather records by carefully accounting for such changes when documentation exists as to the date and nature of the change. For the U.S., the National Climate Data Center has produced a dataset of carefully adjusted, quality-controlled climate data called the U.S. Historical Climate Network[11]. The results reported here are based on USHCN records for temperature and precipitation.

2.2.1 Temperature

Evaluation of long-term temperature records for the Pacific Northwest shows substantial warming for almost every long-term record of climate in the Pacific Northwest during the 20th century[12]. Trends were largest in the region west of the Cascade Mountains and largest everywhere in winter and spring[13]. For stations in the Puget Sound region in the November-March period (Figure 4), a majority of trends over the whole record at the station (typically >80 yr) lie between 0.09°C/decade and 0.16°C/decade, and a majority of trends 1950-2000 lie between 0.23°C/decade and 0.28°C/decade[14]. As larger-scale studies have shown, urbanization and the consequent transformation of the environment around some weather stations from fields and forests into warmer blacktop have played a minor role in temperature trends: stations in and near urban areas have trends that are similar to those in rural areas. The same is true in the Puget Sound area.

As a complement to the spatially distributed but temporally simplified view just presented, we consider the variations in time of a regionally

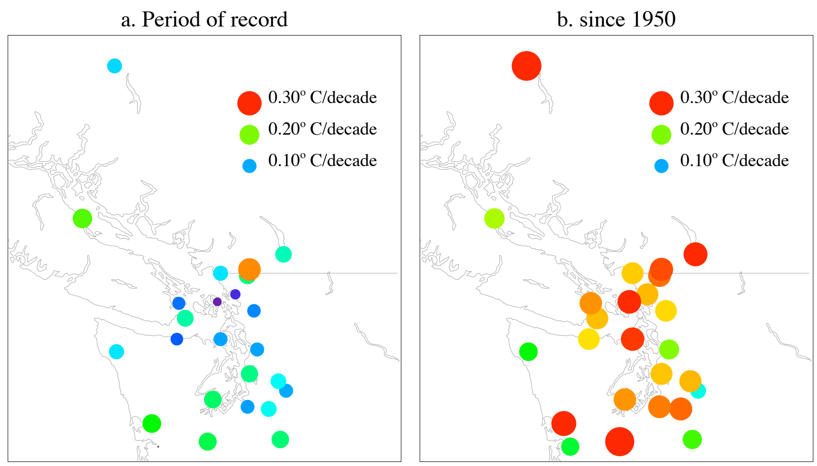


Figure 4. Linear trends in November-March temperature. The left panel shows the trend over the entire period of record for each station, and the right panel shows trends 1950-2000. All trends are positive and the magnitude of the trend is indicated both by the area of the circle and by the color. Reprinted from Mote (2003b).

[11] Karl et al. 1990.

[12] Mote 2003a.

[13] ibid. The larger warming in winter and spring is commonly observed around the world and is attributable in part to "feedbacks"; for example, if a small amount of warming melts snow, the surface can absorb more sunshine and warms further.

[14] Mote 2003b.

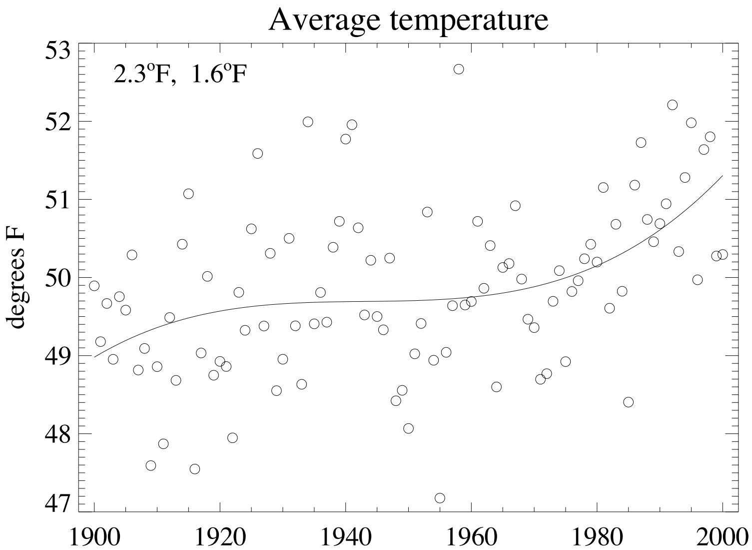


Figure 5. Yearly average temperature for the Puget Sound region (formed by averaging observations from five representative climate monitoring stations in the Puget Sound region). The smooth curve (a cubic fit to the data) indicates that average temperature increased 2.3°F from 1900 to 2000 and 1.6°F from 1950 to 2000.

averaged temperature time series. Since climate stations tend to be clumped in certain areas, simply averaging them would not provide a true regional average of temperature or precipitation. A regional average for Puget Sound (Figure 5) can be constructed by selecting a smaller number of evenly distributed stations[15]. As for the whole Pacific Northwest[16], warming in this region was greatest for winter (January-March) and least for autumn (October-December), and the greatest warming has occurred in the last 30 years. For the annual average, 20th century warming in Puget Sound was 1.5°C (2.3°F), substantially greater than the warming for the whole Pacific Northwest (0.8°C) and globe (0.6°C) over the same period. All ten of the coolest years occurred before 1930, and six of the ten warmest years occurred since 1990, with 1992 the warmest overall and the warmest in both January-March and April-June.

The three warmest winters, 1992, 1983, and 1998, all occurred during a tropical El Niño event. El Niño events typically bring warmer winters to the Pacific Northwest, as does a warm phase of the Pacific Decadal Oscillation (PDO)[17]. An important question is the role that El Niño or PDO might have played in 20th century trends. In order to answer that question, Mote (2003a) regressed seasonal PNW temperature records on a time series of the North Pacific Index (NPI)[18], which reflects variability of both PDO and El Niño through their influence on changing atmospheric circulation over the North Pacific and PNW region. This regression analysis shows that the NPI accounts for about 40% of the large 20th century warming trend in winter, but has little influence over trends in other seasons.

Several studies of temperature trends, usually on the national scale and using data aggregated up to a scale of 5° longitude × 5° latitude (approximately the area of the state of Washington), have produced numbers similar to those mentioned above. Zhang et al. (2000) found that southern British Columbia warmed substantially (roughly 0.5°-1.5°C) during the 20th century, with warming greatest for daily minimum temperature and for wintertime, and precipitation increased in all seasons, in amounts between 5 and 35%. WLAP (2002) found warming rates of 0.8°C per century in spring, 0.5°C per century in autumn, and no trend in summer and winter in Georgia Basin (1895-1995). These trends were dominated by increases in minimum temperatures, which were at least 0.7°C per century in all seasons.

A key point for ecosystems is the asymmetry of trends found in all of these studies. Warming rates are largest for lowest temperatures, i.e., daily minima and winter. The likelihood of very cold temperatures (which serve to control certain pests but also can damage certain plants) de-

[15] Mote 2003b.

[16] Mote 2003a.

[17] Mantua et al. 1997. More information on the PDO, and up-to-date values for the time series, can be found at jisao.washington.edu/pdo/

[18] Trenberth and Hurrell 1994. The NPI is an average of sea level pressure over a certain area of the North Pacific, and tends to be low when ENSO or PDO indices have negative values.

clined much more rapidly than the likelihood of very high temperatures increased.

2.2.2 Precipitation

While changes in temperature over recent decades have been uniformly and consistently positive, changes in precipitation in the Puget Sound region are best characterized by fluctuations on a wide range of timescales with no clear trend, and by higher spatial variability than temperature[19]. One simple statistic to illustrate this difference between temperature and precipitation trends is the ratio of the observed trend (τ, calculated as the slope of a linear fit) to the interannual standard deviation (σ). For the Pacific Northwest as a whole, the τ/σ ratio of annually averaged temperature over the 20th century is 1.6, but for annual precipitation the trend is +14%[20] and the τ/σ ratio is only 0.7. That is, the temperature trend stands out considerably above year-to-year variations but the precipitation trend does not.

This difference in the magnitude of trend (compared with variability) has two implications. First, human influence on precipitation will take longer to emerge from natural variability than human influence on temperature; future precipitation trends are inherently harder to predict because of this variability. Globally, human influence on precipitation has not yet been detected and probably will not be for at least a decade, whereas human influence on temperature was detected a decade ago[21].

There is little indication, as we will see in section 2.3, that annual and interannual variations in precipitation in the 21st century will be vastly different from those in the 20th century. Second, properties or characteristics of the living and non-living environment (e.g., streamflow, salinity, phytoplankton abundance, timing of salmon migration) that respond to precipitation have probably already experienced the range that they will experience in the next century, whereas those that respond to temperature are likely to continually encounter new conditions.

2.3 21st century climate change in the Puget Sound Region

Sometimes the past can be used to predict the future. Unfortunately, there is no analog for 21st century greenhouse gas concentrations either in human experience or in the paleoclimate record since 20 million years ago. Instead, we must rely on simulations of future climate using numerical models of the climate system, "climate models." By applying the laws of physics and representing the atmosphere, ocean, and land surface as a set of discrete grid boxes, it is possible to simulate present-day climate with reasonable fidelity. For example, several models that we examined simulated the annually averaged temperature of the Pacific Northwest to within 2°C, correctly simulated the seasonality of precipitation (the observed ratio of October-March precipitation to April-September precipitation is 2.43, and the models got a ratio of 2.21 to 2.44), and correctly simulated the 20th century trend (0.7-0.9°C, observed 0.8°C)[22].

In order to use these models to simulate future climate, some estimates of future greenhouse gas levels are required. By considering a range of scenarios of future human population, socioeconomic development, technologies, and energy choices, Nakicenovic et al. (2000) derived dozens of possible future pathways, which lead (for example) to changes in CO2 during the 21st century from 369 ppmv in 2000 to anywhere from 549 to 970 ppmv, or an increase of from 100% to 250% above pre-industrial levels, in 2100. However, the economic inertia (e.g., the typical lifespan of a large coal-fired power plant) actually produces little difference in climatic forcing among these scenarios by 2050. The "radiative forcing" (additional heat provided by the additional greenhouse gases) ranges from 2.90 to 3.81 W/m^2.

The larger uncertainty during the next half-century concerns the climatic response to such forcing. Recent work by several groups of scientists[23] suggests that the climate might be more sensitive than previously thought – that is, the globally averaged warming resulting eventually from a doubling of carbon dioxide (the "climate sensitivity") might be greater than the 1.5-4.5°C range previously acknowledged. The climate

[19] Mote 2003b.

[20] Mote 2003a.

[21] See, e.g., Gillett et al. 2004.

[22] Mote et al. 1999.

[23] Andronova and Schlesinger, 2001; Forest et al., 2002; Gregory et al., 2002; Murphy et al., 2004; Stainforth et al., 2005.

models used here were developed and run by research teams at institutions around the world[24] and have a climate sensitivity in the usual range. The simulations here used two scenarios of future greenhouse gas concentrations known as A2 and B1, representing high-growth and low-growth scenarios. The increase in CO2 from 1970 to 2000 averaged 0.40%/year, though other gases had different rates. (The rate itself is rising, though, as energy consumption outpaces population growth.) Continued increase at 0.4%/year would lead to a concentration of 456 ppmv in 2050, below the low end of the IPCC scenarios.

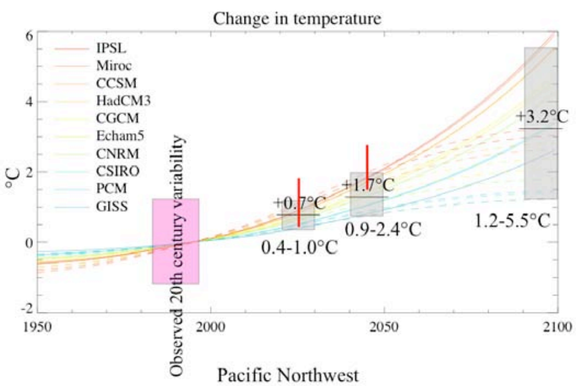


Figure 6. Expected changes in regionally averaged temperature for the Pacific Northwest, for the 2020s, 2040s and 2090s relative to the 1990s. The original model output has been smoothed. Red lines show range of change for the previous generation of scenarios, differences mostly due to how the baseline was calculated. These smooth curves indicate the slow drift in averages, about which natural variability will continue to occur.

Global climate models typically use coarse spatial resolution that does not include important topographic features that influence Northwest climate, like the Cascade and Olympic mountains. It could be argued that model output is unsuitable for extracting estimates of regional climate change even at the scale of the whole Pacific Northwest, let alone the Puget Sound region. However, experiments with higher-resolution regional climate models suggest that although the mean climate is much better simulated with regional models, the changes in climate are very similar for regional and global models. The greater availability of global model output and the need to provide estimates of the range of uncertainty leads to the choice of examining regional output from a large number of global models.

2.3.1 Future temperature

The climate models project an average warming rate for the Pacific Northwest of 0.34°C (0.6°F)/decade for the period 1990s-2040s (Figure 6). The lowest rate of warming is about 0.2°C (0.5°F)/decade, and the highest is 0.5°C (0.9°F)/decade. Previous scenarios (red bars in Figure 6) had higher rates of warming, partly because of a mismatch in baseline climates and partly because the greenhouse gas scenarios used had unrealistically high growth rates.

It is important to note that because of lags in the climate system (for instance, ocean uptake of heat), if concentrations of greenhouse gases in the atmosphere were stabilized, warming would still continue for decades. Sea level rise would continue for centuries as the warming ocean continued to expand.

2.3.2 Future precipitation

Global precipitation is not simulated as well by climate models as global temperature[25] and, as noted above, a human influence on global precipitation has not been detected. Rather, global precipitation seems to respond more to "shortwave" (visible) radiative forcing, especially as influenced by volcanic eruptions. In addition, on a regional scale, precipitation is highly sensitive to atmospheric circulation and varies substantially on all time scales from daily to annually. These factors taken together make the simulation of future changes in precipitation in a warming climate more problematic than temperature.

Most models suggest modest (0-20%) increases in winter precipitation and in annual precipitation by mid-21st century. Changes in summer precipitation tend to be slightly negative, though simulated changes in precipitation are smaller than the increases in evaporation. None of these changes stands out above background variability, and model simulations have large interdecadal variability so that the ten-year averaged changes commonly reported are not necessarily indicative of a monotonic trend or of anthropogenic influence.

[24] For details and references see Mote et al. 2005.

[25] McAvaney et al. 2001.

3 Snowpack and Streamflow

3.1 Observed (20th century) change in snowpack and streamflow

In much of the West, hydrologic changes have been observed in the past 50 years that are consistent with atmospheric warming, especially in winter and spring in snowmelt-dominated river basins[26]. These changes include reductions in spring snowpack, earlier spring snowmelt run-off, increases in winter flow, and decreases in summer flow. Most of these changes have been quantitatively linked to rising temperatures[27].

In the Puget Sound area, Mote (2003b) examined 20th century fluctuations and trends in snow water equivalent (SWE) which has been monitored at several sites ("snow courses") since the 1940s. All 20 of the locations in Washington that represent Puget Sound drainages showed declines in April 1 SWE since 1950, most (especially those at lower elevations) in excess of 25%. These declines depended on elevation; Figure 7 shows representative data for a low-elevation and high-elevation snow course, with steeper declines at the lower elevation.

The early 1950s were, however, an unusually cold and snowy period in the region, and Mote (2003b) reconstructed SWE on the basis of climate records in order to deduce whether the declines in SWE were unusual. At most snow courses, SWE apparently increased from 1905 to 1950 owing to increasing precipitation, whose influence exceeded that of rising temperatures. Declines since then occurred partly as a result of increasing temperatures and partly from declining precipitation. Hamlet et al. (2005) showed that for the Cascades as a whole, roughly half the declines since 1950 were due to increases in temperature and half due to decreases in precipitation, but the decline since 1916 was almost entirely due to rising temperatures.

As noted in the introduction, most of the major rivers in the Puget Sound basin have been dammed and operation of the dams may have a significant influence on streamflow. Most studies examining trends in streamflow[28] use data from unregulated basins. In the Puget Sound region, the two largest unregulated basins are the Skykomish and Snoqualmie and the Nooksack

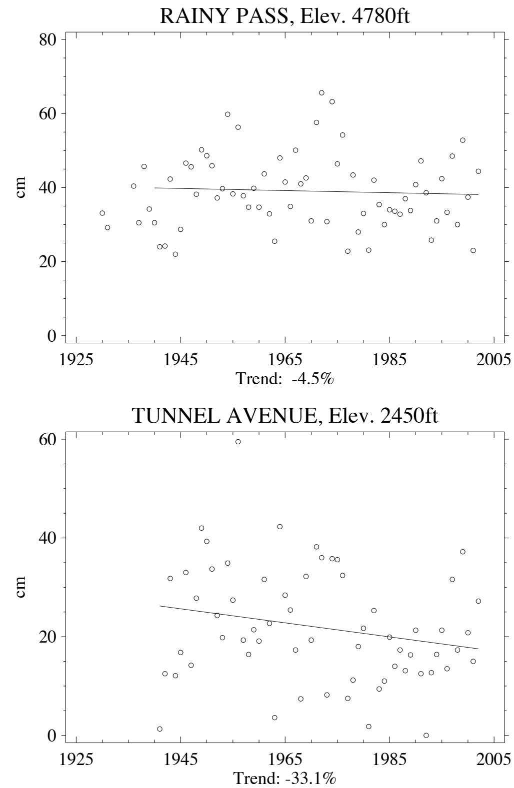


Figure 7. April 1 snow water equivalent at two locations in the Cascades, one at high altitude with no long-term trend and one at low altitude with a large decline.

(Table I). The largest basin, the Skagit, has several reservoirs including Ross Lake, the largest in western Washington.

Daily data were obtained and arranged by water year (for example, Water Year 2001 spans the period October 1, 2000 through September 30, 2001). In this analysis[29], the quantity of most interest is the total inflow to Puget Sound for water years 1948-2003, which is formed by summing the daily flow of all of the rivers in Table 1 that satisfy quality screening. The Nisqually, Deschutes, and Samish were omitted because they each have several years of missing data. The Skagit was omitted because of the effects of regulation; it is hoped that a future analysis will account for the effects of regulation and include the region's largest river.

[26] Cayan et al. 2001, Mote et al. 2005, Regonda et al. 2005, Stewart et al. 2005.

[27] Mote et al. 2005, Cayan et al. 2001, Stewart et al. 2005, Hamlet et al. 2005.

[28] Lins and Slack 1999, Groisman et al. 2001, Stewart et al. 2005.

[29] For details, see Mote and Hamlet 2005.

Table I. USGS gages in Puget Sound drainages[30]

River	Location	Drainage area (mi^2)	Mean annual flow (cfs)	Period of record
*Skagit	Mt Vernon	3093	16,623	1940-2003
Snohomish†	Monroe	1537	9,593	1964-2003
*Puyallup	Puyallup	948	3,308	1915-2003
Nooksack	Ferndale	786	3,806	1967-2003
*Nisqually	McKenna	517	1,292	1948-2003
Stillaguamish	Arlington	262	1,896	1929-2003
Green	Auburn	399	1,340	1936-2003
*Skokomish	Potlatch	227	1,215	1944-2003
*Cedar	Renton	184	654	1946-2003
Deschutes	Rainier	89.8	261	1950-2003
Samish	Burlington	87.8	244	1944-2003
Duckabush	Brinnon	66.5	417	1939-2003

*River or a major tributary is dammed.

† The Snohomish is formed by the confluence of the Snoqualmie and Skykomish, which are used in sum for analysis 1940-2003. They contribute respectively about 4000 cfs each. The Snohomish gauge at Monroe is 0.1 mi below confluence of Snoqualmie and Skykomish.

** There was a gauge on the Deschutes River at Olympia from 1946-1963. Mean flow during that time was 403 cfs, compared with 268 at Rainier, for a mean factor of 1.50.

Total freshwater inflow to Puget Sound (Figure 8) shows the following trends:

1. Total annual inflow has declined 13% owing partly to changes in precipitation (-5% over 1948-2003); both may be related to the change in phase of the Pacific Decadal Oscillation (PDO) in 1977. PDO phases influence the statistics of winter precipitation in the Pacific Northwest, such that warm phase years tend to have below-average precipitation; the period 1977-1997 was marked by a preponderance of warm-phase years and slightly below-average precipitation for the PNW.
2. The streamflow midpoint, i.e., the date at which half the water year's flow has passed[31] has shifted earlier in almost all rivers in Table I, and for the sum of the flow of all the rivers the midpoint has shifted by 2.1 days per decade, or 12 days;
3. Owing to the declining role of snow storage, the amount of streamflow entering Puget Sound between June-September as a fraction of total streamflow for the water year flow has declined from 25.4% to 20.8%, a decline of 18%;
4. The likelihood of mean annual flood (roughly the highest average daily flow) has increased, despite the decline in annual inflow; and
5. The likelihood of seeing the lowest 1% of daily flow in any given year has also increased substantially.

With the exception of (1), which can be attributed to climate variability associated with the Pacific Decadal Oscillation and is not necessarily a feature of future climate change, these results are consistent with the projected regional impacts of global warming.

In addition, most of the glaciers of the Cascades and Olympics have been retreating during the past 50-150 years in response to warming (Figure 9). Their aggregate input to Puget Sound is miniscule, but in higher reaches of certain river basins like the Nooksack, melting glaciers provide a substantial portion of the flow in late summer.

[30] Source: waterdata.usgs.gov. USGS gauge numbers, in order as they appear in the table: 12200500, 12150800, 12101500, 12213100, 12089500, 12167000, 12113000, 12061500, 12119000, 12079000, 12201500, 12054000.

[31] see, e.g., Stewart et al. 2005.

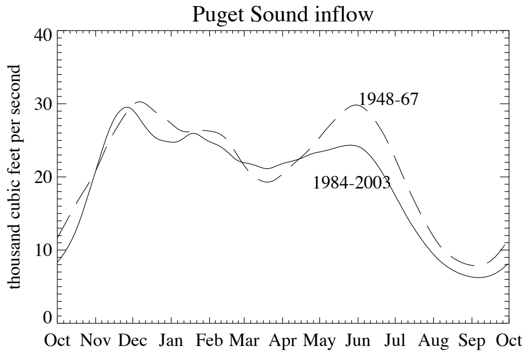
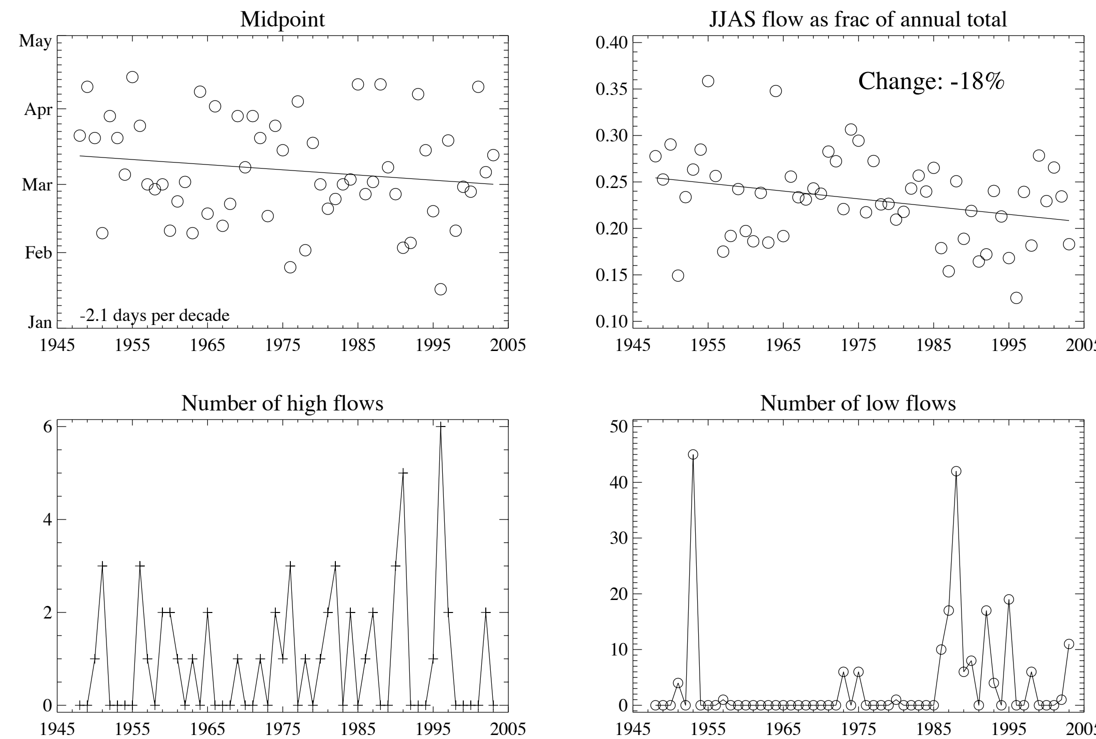


Figure 8. Statistics of the total river flow into Puget Sound from most of the gauges listed in Table I. (a) smoothed daily flow for the first 20 years and last 20 years of the record. Note the decline in spring flow. (b) date at which half the water year's flow has passed. (c) Fraction of annual flow in the months June through September. (d) number of times per year that daily flow exceeds the mean annual flood (see text). (e) Number of times per year flow falls below the 1st percentile for daily flows.



3.2 Future changes in snowpack and streamflow

In a preliminary assessment, we have examined the temperature sensitivity of the timing of total freshwater inputs to Puget Sound. These results are produced using the macro-scale Variable Infiltration Capacity (VIC) hydrologic model implemented over the PNW at 1/8th degree resolution. The model is run for the current climate (1916-2003), and for two simple climate change scenarios, +1.7°C and +2.5°C. The scenarios are also somewhat wetter in winter (especially the +1.7°C scenario) and somewhat drier in summer overall. These simulations do not assess the effects of potential changes in deep ground water, land use, consumptive water use, or water management, all of which may potentially alter these results to some degree. Our intention here is not to quantify these cumulative impacts in great detail, but rather to make the case that the timing of fresh water inflows to the Sound is extremely sensitive to warming temperatures.

Water balance components averaged over all the VIC grid cells in the Puget Sound region are shown for each month (Figure 10) for the current climate, +1.7°C scenario, and +2.5°C scenario. The diagram includes both storage terms (soil and SWE) and flux terms (precipitation, runoff, and evapotranspiration). The peak precipitation occurs in December, but the simulated peak runoff and peak soil moisture occur in June owing to the delaying action of snow storage, which peaks in April. Evapotranspiration peaks in July and then declines as the soil moisture declines.

Figure 11 focuses on the runoff component for the current climate, 2020s, and 2040s. As is common in snowmelt-dominated river basins, predicted streamflow declines substantially in summer and increases substantially in winter, with lower snowpack, lower summer soil moisture, and earlier peak streamflow. Late summer

Figure 9. South Cascade Glacier in 1928 (left) and in 2000 (right). Figures courtesy of Dr Ed Josberger, USGS Glacier Group, Tacoma, WA.

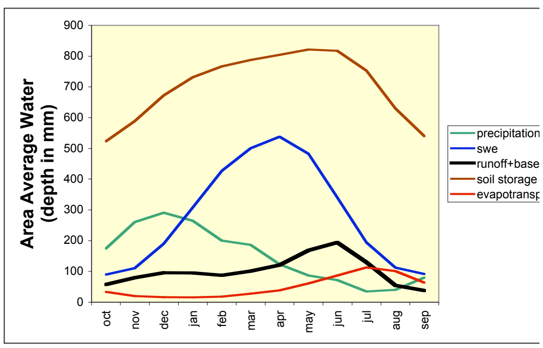


Figure 10. Mean annual variation of several quantities in the hydrologic cycle, averaged over the Puget Sound basin, from the VIC hydrologic model. Water "storage" terms - soil moisture (brown) and snow (blue) - are shown along with "flux" terms - precipitation (green), runoff (black), and evapotranspiration.

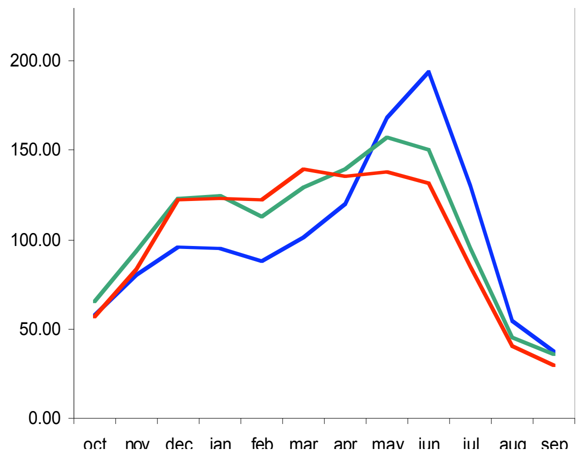


Figure 11. Changes in average runoff for the Puget Sound basin from the VIC simulation, for 20th century climate (blue), 2020s (green), and 2040s (red). Note the projected declining summer flow, which matches observed changes (Figure 8).

low flows in a warmer climate are also likely to be reduced, because of systematic changes in late summer soil moisture due to an effectively longer summer season from snowmelt to fall rains (Figure 10). For a warming of about +1.7 C, for example, runoff from October to March increases by about 25%, and from April to September runoff decreases by about 12%. For a warming of +2.5 C, runoff from October to March also increases by about 25%, and from April to September runoff decreases by 21% (Figure 11). Note that the summer flows are significantly different in the two scenarios, but the winter flows are about the same overall. This effect is partly due to differences in the precipitation scenario in the fall and winter in each scenario which produce direct runoff over fairly large low elevation areas.

3.3 Flooding

In almost every river basin in the Puget Sound region, flooding occurs following heavy rains in fall or winter, but some of this rain falls as snow at high elevations, reducing immediate runoff and flooding. Future warming will reduce the flood protection currently provided by snow and may increase the total winter precipitation. More important, a number of studies suggest that intensity of precipitation – e.g., the likelihood of >2" of rain in 24 hr – will increase in a warming climate[32]; increases in rainfall intensity have already been observed in most of the U.S. but not yet in the Northwest[33]. There is some suggestion (Figure 8) that the likelihood of flooding has increased, but this could well reflect changes in land cover. Taken together, these changes suggest that flooding for Puget Sound's rivers may become more likely.

Most urban areas located on river mouths are protected by upstream flood control reservoirs or were developed sufficiently far above the waterline to protect against flooding. Some urban areas, e.g., Olympia (Deschutes River mouth on south Puget Sound), lack both flood control reservoirs and adequate freeboard (altitude above high tide), and thus are subject to periodic flooding. Agricultural districts in river deltas (especially the Skagit) are typically protected by dikes; occasionally, high river flows on a high tide result in breaches of the dikes and flooding, such as the November 1990 Fir Island flood in the Skagit River delta on north Puget Sound[34]. Numerous Skagit river levees were overtopped and damaged as a result of two large November rain storms in November 1990. Fir Island, located between the two forks of the Skagit River and surrounded by marine dikes on Skagit Bay and river levees along the Skagit River, experienced extensive damage when the Skagit River breached a levee and flooded the island. The marine dikes had to be intentionally breached to provide an exit point for the river water. Tidal influence may have contributed to the levee breaching, as the levee is located within the tidal zone of the Skagit River (Graham 1992).

The severity of floods and shorelands erosion events dramatically increases with the coincidence of several risk factors, e.g., accelerated sea level rise combined with high river flows. In several locations in coastal Skagit County, for example, the Federal Emergency Management Agency's Flood Insurance Rate Maps indicate the difference in elevation between a "100 year flood" and a "10 year flood" to be approximately 30 cm. If the normal sea level were to rise 30 cm, events which were previously estimated to have a one percent chance of occurring in any given year would instead have a 10% of occurring each year.

4 Physical environment of Puget Sound waters

4.1 Sea level and the coastline

Sea level in Puget Sound varies on a variety of timescales. Besides the familiar tidal cycle, sea level can also vary from season to season and from year to year. In general, seasonal variations in sea level reflect seasonal variations in regional atmospheric pressure and wind patterns. Local sea level also reflects inter-annual variations in local atmospheric pressure and alongshore wind stress[35], storm events, rainfall and river runoff, long wave propagation of ocean waves[36], the cycling of Perigean tides[37], integrated water column density, and thermocline depth[38]. El Niño events

[32] E.g., Kharin and Zwiers 2000.

[33] Groisman et al. 2004.

[34] Johnson 1998.

[35] Chelton and Davis 1982, McConnaughey et al. 1994.

[36] Hickey 1989.

[37] Perigean tides are those which occur when the earth, the moon, and the sun are in alignment, and the moon is at the point in its orbit closest to the earth (Perigee), thus producing the highest tides of the lunar tide cycle. See Bascom (1964) and Wood (1986), and note the common misunderstanding about Perigean spring tides resulting from Wood's 1978 book (http://co-ops.nos.noaa.gov/faq2.html#15).

[38] Bailey et al. 1995.

are known to elevate sea level along the west coast of the United States through a combination of changed wind patterns and long ocean waves.

4.1.1 Observed (20th century) sea level change

Over the last century, global sea level has been increasing: observed global sea level rise during the past century has been in the range of 1.0 to 2.0 mm/yr (4-8 inches per century)[39]. Global sea level rise has resulted from the warming and therefore the thermal expansion of ocean waters, plus the melting of glaciers, small ice fields, and polar ice sheets. In Puget Sound, manifestation of global sea level rise is affected by a variable pattern of land subsidence and uplift caused by tectonic processes associated with subduction of the offshore Juan de Fuca Plate under the North American Plate, and glacial rebound following the retreat of glaciers at the end of the last glacial age[40]. In Puget Sound (Figure 12), land subsidence ranging from zero in eastern Strait of Juan de Fuca and north Puget Sound (Bellingham Bay, San Juan Islands, Dungeness Bay) to 2 mm/yr (8 inches per century) in south Puget Sound with a maximum at Tacoma[41] produces a local sea level rise that is greater than the global average[42] Thus, net local sea level rise in north Puget Sound is close to the global average, and is up to double the global average in south Puget Sound.

Puget Sound shorelines have been affected by slow, chronic erosion of unconsolidated and poorly consolidated shorelines over the past century (probably fractions of an inch per year). “The common response to shoreline erosion – real or apparent – has been a proliferation of bulkheading and other `hard protection' techniques....Extensive shore protection will minimize shoreline erosion and retreat, but will also eliminate the source of materials which would otherwise be available to maintain beaches and accreting shorelines.”[43]

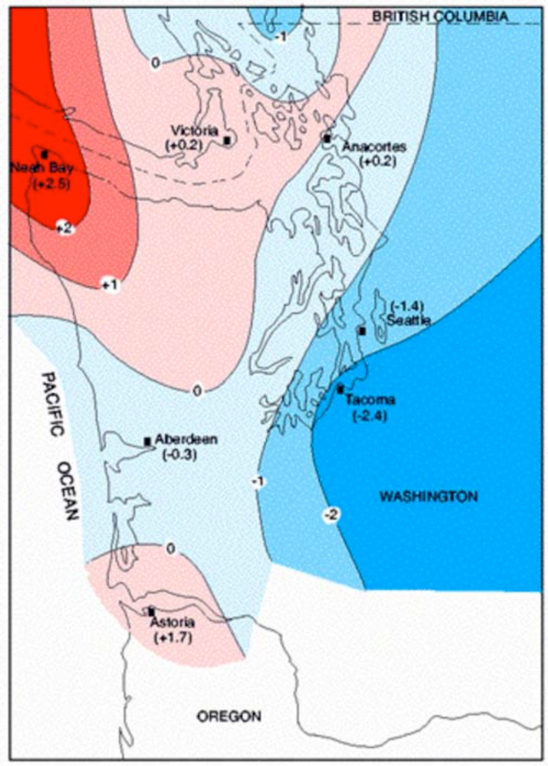


Figure 12. Rates of sea level rise relative to the global average (in mm/yr), with blue indicating negative and red positive. From Canning (1991).

Bluff landsliding is fairly widespread in the glacially deposited steep hillsides around Puget Sound (Figure 13); nearly a third of the Puget Sound shoreline is unstable[44]. Landsliding is

[39] Church et al. 2001.

[40] Holdahl et al. 1989, Mofjeld 1989.

[41] Canning 1991.

[42] Shipman 1989.

[43] Canning 1991.

[44] Downing 1983.

typically associated with heavy winter rainfall[45], although the actual risk of landsliding depends on a variety of factors in a given location, including the local geological characteristics, the recent history of landslides, and the degree and nature of site modification[46] that occurred during land development. In Puget Sound, for example, landslides tend to occur when heavy rains saturate sand layers above silt or clay beds, or clay-rich glaciomarine deposits, resulting in slope failures. When the toes of such bluffs are exposed to the water surface, they may be even more vulnerable to undercutting by wave erosion.

Figure 13. Eroded bluff on the south end of Whidbey Island. Note the suspended concrete structure on the left of the photo, a remnant of WWI-era Fort Casey. Photo credit: Philip Mote.

4.1.2 Future

Perhaps the best understood component of future change in the coastal marine environment is the accelerated sea level rise that will occur as a result of both past and future greenhouse gas emissions. Projections of global sea level rise by the Intergovernmental Panel on Climate Change in the 21st century are 0.09-0.88 m (3.5-35") (Figure 14), compared with 1.0-2.0 mm/yr (4-8") observed during the last century[47].

Regional sea level rise is expected to vary from the global average as a result of a variety of factors: oceanic winds, coastal winds, local changes in atmospheric pressure patterns, isostatic rebound, tectonic processes, and regional differences in thermal expansion rates of ocean water[48]. For example, the CGCM1 climate model projects a global sea level rise due to thermal expansion of 0.45m (18") by 2100,[49] but with strong regional differences. Sea level rise in the eastern Pacific Ocean, off the coast of British Columbia and the PNW, is projected to be 0.2 m (8") higher than the global average, or 0.65m (26") higher by 2100[50]. Another climate change scenario (from the Hadley Centre's HadCM2 model) also projects greater increases in sea level over the next century for the Pacific coast of North America than for the Atlantic coast. Thus, in general, sea level rise in Puget Sound can be expected to proceed at a more rapid pace than the global average rate of increase, especially in the subsiding central and southern Puget Sound areas.

Sea level rise and other climate-driven changes could affect the physical environment along the shorelines of Puget Sound in numerous ways. "To the extent that sea level rise acceleration occurs, coastal bluffs which are now subject to landsliding caused by shoreline erosion and undercutting will experience an increased rate of slope failures. Erosion and undercutting may be extended to other areas."[51]

Saltwater inundation of low-lying estuaries and an upriver migration of tidewater will reduce and in some cases eliminate estuarine habitat that now lies between the Sound and dikes or levees. Saltwater intrusion could affect aquifers near shorelines, particularly important in island locations where surface sources of water are limited.

The modest increases in winter rainfall that is projected by most climate models suggests a future increase in saturated soils and therefore landslides. An increased frequency and/or magnitude of landsliding could be expected anywhere

[45] Gerstel et al. 1997, Tubbs 1975.

[46] Site modification embraces a suite of activities associated with land development and use, including initial vegetation removal, earth moving (cutting and filling) to reshape the site, the manner in which surface and subsurface drainage of storm water is handled, and long-term vegetation management practices.

[47] Church et al. 2001.

[48] Thompson and Crawford 1997; Hengeveld 2000; Church et al. 2001.

[49] Note that this sea level rise projection value is due to thermal expansion only, and does not include melt water from glaciers or ice fields.

[50] Hengeveld 2000.

[51] Canning 1991.

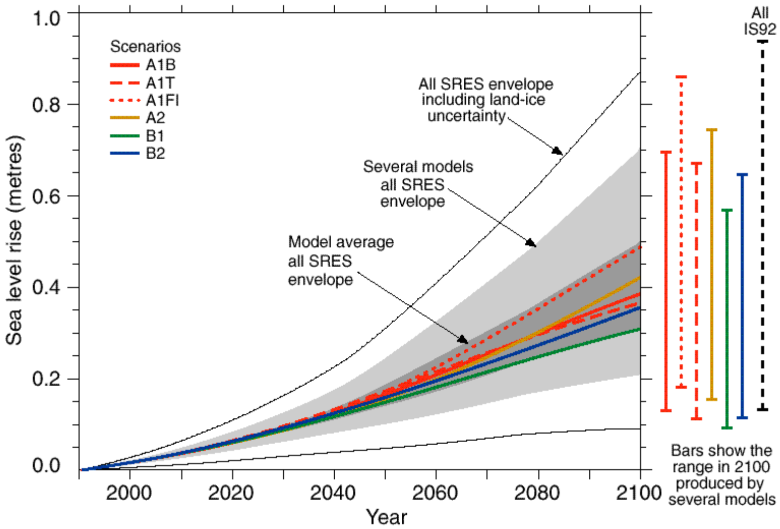


Figure 14. Estimated global sea level rise from 1990 to 2100 for a range of assumptions about socioeconomic development (colors) and for a range of climate sensitivity (roughly indicated by the span of bars on the right). From IPCC

the geologic conditions are conducive to landsliding, and are likely to be even more severe in areas subject to intensive development on unstable slopes. Within Puget Sound the cyclic interaction of beach erosion and bluff landsliding is expected to be exacerbated by sea level rise (more beach erosion) and heavier winter rainfall (more landsliding).

Shoreline retreat rates for bluff-backed shorelines have been determined for only a few locations in northern Puget Sound. Keuler (1988) found that although a high percentage of the bluff-rimmed shoreline in this area is eroding, the amount of erosion varies considerably from one shoreline segment to another in terms of bluff retreat rates, volume of bluff material lost, and longshore extent of eroding zones. Keuler reports long-term (greater than twenty years) average shoreline retreat rates at locations exposed to long wind fetches (and therefore high wave energy) in the range of 10 to 34 cm/year. At sheltered shoreline locations (more common in Puget Sound) shoreline retreat is in the range of 1 to 10 cm/yr. Shoreline retreat of bluff-backed shorelines is an episodic process, not a chronic process. At any particular location landslide events usually occur at intervals of many years to decades apart.

The vulnerability of the coastal environment to permanent inundation resulting from sea level rise depends on a number of factors, including beach slope, vertical land movement due to tectonic processes, and the adaptability of the affected ecosystem or human social system.

Possibly the only study of the potential for inundation due to sea level rise in the PNW is one completed for the City of Olympia[52]. Olympia is situated in the portion of Puget Sound experiencing the highest rates of subsidence (Figure 12). Olympia was considered by the Washington Department of Ecology, which funded the study, to be representative of low-lying urban areas at river mouths.[53] At the study's 1990 base line year, 14.5 hectares fringing the City's shoreline were subject to a 100-year flood. By 2100, the area subject to flooding, primarily the Port of Olympia peninsula, would increase 4.6-fold to 66.3 hectares at the existing (historical) rates of sea level rise and local land subsidence. Coincidentally, this same area would be permanently inundated under the study's climate change-induced sea level rise scenario.[54] Under the climate change scenario, an additional 60.0 hectares, primarily Olympia's central business district, would be subject to the 100-year flood. The most significant impact on the city of Olympia was a projected increase in the frequency and severity of flooding in the downtown area; other potential impacts included increased infiltration and hydraulic surcharging of the sewage system, increased risk of damage from seismic events, potential salt water seepage into drinking water

[52] Craig 1993.

[53] Other similar conditions might be found on Puget Sound at discontinuous portions of the Mukilteo – Everett – Marysville area; and at Bellingham.

[54] The rates of sea level rise used in the Olympia study were adjusted to exact feet for convenience of use with the City's topographic mapping at 1-foot (30.5 cm) contour intervals. The combined rate of existing sea level rise and local subsidence was adjusted to 1.0 foot by 2100. The combined rate of climate change-induced sea level rise and local subsidence was adjusted to 4.0 feet by 2100, based on the then-current mid-range global sea level rise scenario of 100 cm by 2100, i.e., about double current estimates.

supplies, increased risk of corrosion and leakage of underground storage takes and pipes resulting in contamination, and increased risk of erosion, landslides, and habit loss along the shoreline of Budd Inlet. Ironically, the area subject to both inundation and flooding under the climate change scenario closely approximates the extent of the tideflats filled for development of Olympia after its founding in 1850.

"River deltas are maintained in equilibrium with existing sea level rise by means of sedimentation. With accelerated sea level rise, the sedimentation rate of only the largest rivers (e.g., the Skagit) is expected to be sufficient to maintain an equilibrium[55]. The deltas of the smaller rivers will be subject to erosion and inundation." (Canning 1991)

4.2 Circulation of Puget Sound

The salinity, temperature, and various aspects of water quality are strongly influenced by the circulation of water. Puget Sound (Figure 1), a glacially carved valley, is separated from the Strait of Juan de Fuca by a shallow (44m, 144 ft) sill at the north end of Admiralty Inlet that reduces exchange of water between the Strait and Puget Sound[56]. The sill also provides a locus for tidally driven local mixing. Sub-basins of the Sound include Whidbey Basin; Hood Canal, which has the slowest circulation of the sub-basins; South Sound, which is most affected by north-south wind; and the Main basin.

Water circulation in Puget Sound is dominated by the inputs of freshwater at the surface, which must be balanced by inflow of salty water at depth, and by tidal stirring especially at the sill at Admiralty Inlet (Figure 15). "Typical of a fjord type estuary, net motion of surface water in Puget Sound is seaward..., and net motion of deep water is landward"[57]. Both deep-water exchange into Puget Sound at Admiralty Inlet and river input follow an interdecadal cycle[58]. Owing to the density differences brought by higher freshwater fluxes, inflow of salty water is shallower during cool phase PDO, whereas during warm phase the inflow is nearer the bottom. Tidal stirring can be quite strong, pushing as much as 60% of the surface waters to great depth in the main basin. Whidbey Basin is fairly isolated and receives freshwater input from the Skagit River, the largest in the Sound, and usually has sharp stratification with a shallow (~10m, ~30 feet) relatively fresh surface layer. The numerous arms of the South Sound often have warm surface water in summer. Hood Canal has a very shallow sill at the mouth (~50m, ~160 feet) and is also long, deep and narrow, resulting in slow circulation, causing the southern end to become hypoxic (oxygen-deprived) at depth.

The effects of changes in timing of freshwater input on the circulation, stratification, and mixing of the Sound are largely unknown. The higher freshwater inputs during certain climatic periods (such as the cool phase PDO, 1947-1976) cause the inflow of salty water to be shallower than under

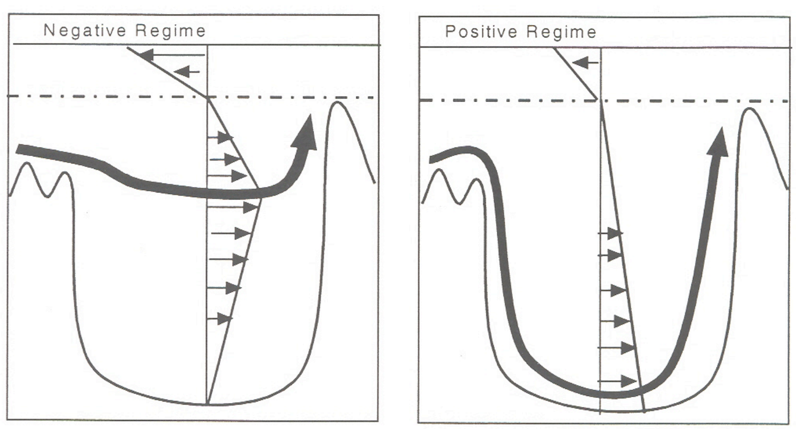


Figure 15. Schematic of current velocity profiles in the Main Basin of Puget Sound, adapted by Pinnix (1999) from Ebbesmeyer et al. 1989. The left frame represents negative phase PDO, and the right frame positive phase. In each frame, Admiralty Inlet is on the left and Tacoma Narrows on the right; small arrows show current velocity, large arrow the approximate route of oceanic inflow.

[55] Hutchinson 1989.

[56] Pinnix 1999

[57] Pinnix 1999, summarizing Ebbesmeyer and Barnes 1980.

[58] Ebbesmeyer et al. 1988.

drier conditions when the inflow is nearer the bottom (*Ibid*). The decrease in freshwater inflow to the Puget Sound-Georgia Basin during the drought of 2000-2001 resulted in a four-fold reduction in the outflow of surface water through the Strait of Juan de Fuca. More detailed modeling studies of these hydrologic effects incorporating ground water, land use changes, water management, etc. are needed to better understand these implications. Some of the tools needed for a more detailed assessment have already been assembled (e.g. as part of the PRISM research effort at the University of Washington).[59] Additional studies assessing the effects to oceanographic processes in the Sound (circulation, mixing, and stratification), water temperature in streams and rivers, sediment transport, and water chemistry will also probably be required to assess impacts to salmonids at various stages of their life cycle in the Puget Sound basin.

4.3 Coastal upwelling

Summertime northerly winds drive coastal upwelling along the Pacific coast, which brings cold, nutrient-rich bottom water to the surface and affects the source salt waters of the Sound. The strength and timing of coastal upwelling show considerable natural variation on timescales from weeks to decades.

Future changes in the upwelling of biologically important nutrients will depend on changes in large-scale atmospheric circulation and local winds. Large-scale winds over the Pacific influence the stratification of the coastal ocean, which determines how easily nutrients can be brought to the surface. Alongshore (local) winds actually drive the upwelling of water in the nearshore region. Some climate models indicate that these crucial wind patterns are relatively insensitive to global warming[60], in contrast to earlier speculation that faster warming over land than over ocean would accelerate alongshore winds. More comprehensive studies of upwelling are limited by the representation of the coastal ocean in current climate models.

5 Water Quality

Changes in water quality can have a significant impact on the physical and biological function of freshwater and marine water bodies. While human influences are often the primary cause of water quality degradation, climate variability and change may exacerbate existing or contribute to new water quality problems when these changes exceed the buffering capacity of the system[61].

Key water quality parameters affecting the physical and biological function of freshwater and marine waters in Puget Sound include water temperature, density stratification, salinity, dissolved oxygen, nutrients, and fecal coliform. Few studies have explicitly examined the impacts of climate variability and climate change on water quality in Puget Sound. The absence of long-term water quality monitoring data in the Sound is a major impediment to conducting these analyses. Segregating the impacts of activities designed to address water quality concerns (e.g., stormwater management regulations, instream flow requirements for salmon) from climate impacts can also be challenging. Our understanding of how climate influences key water quality parameters is discussed in the following sections. It is important to note that the following overview is based strictly on literature review. The CIG has not to date undertaken any comprehensive studies on water quality impacts associated with climate variability and change.

Puget Sound water quality is strongly influenced by the amount and timing of freshwater input (strongly a function of the amount and type of winter precipitation in the PNW); stream, estuarine, and coastal ocean temperatures; and patterns of stratification and mixing between the estuary and the coastal ocean. We use these pathways of influence to project the likely implications of future climate change on Puget Sound water quality.

5.1 Water Temperature

Water temperature is an important determinant for rates of physical, biologic, and chemical processes in fresh water and marine water bodies, including density stratification, salinity, and solubility of dissolved gases. Water temperature is also an important factor controlling the suitability of habitats for freshwater and marine organisms. Twenty percent of the water quality problems identified in the Puget Sound basin in 2004 are related to river temperatures that exceeded critical threshold values.

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[59] www.prism.washington.edu

[60] Hsieh and Boer 1992, Mote and Mantua 2002.

[61] Murdoch et al. 2000.

Data from Ecology[62] for five monitoring sites show that in winter, all five sites have similar sea surface temperature, but in summer, they differ by as much as 5°C (9°F), with isolated southern inlets warmest. These seasonal variations of temperature play an important role in water quality issues.

In freshwater systems, factors contributing to increased water temperature include increases in ambient air temperature, urbanization, reduced stream flows, increased sedimentation, point source industrial discharges, stormwater runoff, diking, loss of riparian vegetation, surface water withdrawals, channelization of rivers and water depth. In the Puget Sound, water temperature is influenced by the temperature of incoming Pacific Ocean water, movement of currents within the Sound, ambient air temperature, and the temperature of freshwater inputs. Sea surface temperature (SST) is also affected by stratification and depth; deep, well mixed monitoring stations in Puget Sound were found to have less seasonal thermal variation than shallow, stratified stations[63].

Long-term records of water temperature for freshwater and marine water bodies in the Puget Sound basin are scarce. One long record is at Madison Park on Lake Washington in Seattle, where measurements of the temperature at various depths have been taken at least biweekly since 1964. Trends in the temperature of the surface (0-10m, 0-33 ft) layer and of the entire water column were 1.5°C and 0.9°C respectively over the 1964-98 period of record[64], or about 0.8°F/decade for the surface layer, faster than the regionally averaged air temperature. An analysis of freshwater temperature data for 1991-2000 found either no detectable trend or decreasing water temperatures at all 22 long-term freshwater monitoring stations in Puget Sound rivers[65], but the shortness of the records makes trend analysis suspect.

There are no long-term measurements of sea surface temperature in Puget Sound itself, but there are some relevant nearby records. Measurements at the Race Rocks lighthouse near Victoria BC date back to 1921 (Figure 16) and indicate decadal-scale fluctuations and a long-term warming trend of 1.7°F (0.9°C) since 1921 and 1.8°F (1.0°C) since 1950[66]. Research using the internal growth rings of geoduck shells as a proxy for sea surface temperature data in the Strait of Juan de Fuca found the 1990s to be the warmest decade in a 154-year period of record for March through October sea surface temperatures in the Strait of Juan de Fuca[67].

Warming of the atmosphere is almost certain to lead to warming of the surface waters of Puget Sound and its tributary rivers and lakes, owing to the strong thermodynamic interactions between surface water and air and the potential for lower summer streamflows. Climate change is also likely to result in a narrowing of annual water temperature range in estuaries (where summer temperatures increase less than winter temperatures because summer temperature is moderated by evaporative cooling)[68].

5.2 Sea Surface Salinity

Sea surface salinity (SSS) is an important determinant of water density. Major influences on SSS in Puget Sound marine waters are the salinity content of Pacific Ocean water entering the Sound through the Strait of Juan de Fuca and

[62] Newton et al. 2002.

[63] Newton et al. 2002.

[64] Arhonditsis et al. 2004.

[65] As noted by the PSWQAT, the reported monitoring results from the 33 monitoring stations can only be considered representative of general watershed conditions. The location of these stations in the mainstem of Puget Sound river systems (rather than tributaries) potentially overlooks localized water temperature problems that may have important implications for habitat management and water quality regulation (PSWQAT 2002).

[66] Data were obtained from Department of Fisheries and Oceans Canada, www-sci.pac.dfo-mpo.gc.ca/osap/data/SearchTools/Searchlighthouse_e.html, and analyzed for this report.

[67] Strom et al. 2004.

[68] Boesch et al. 2000

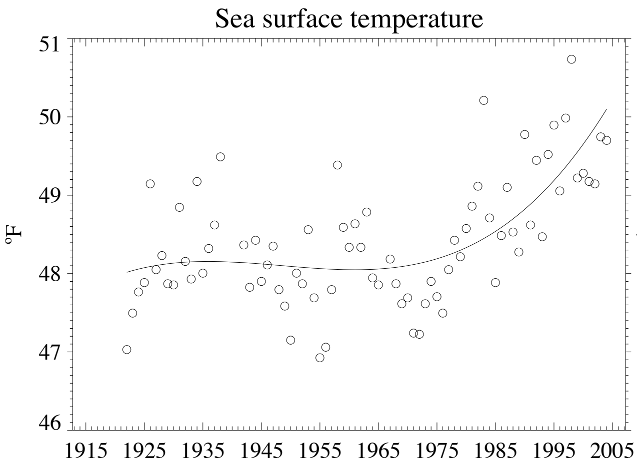

Figure 16. Annually averaged sea surface temperature at Race Rocks, Victoria, BC. The smooth curve is a cubic fit as in Figure 5; most of the warming has occurred since 1970.

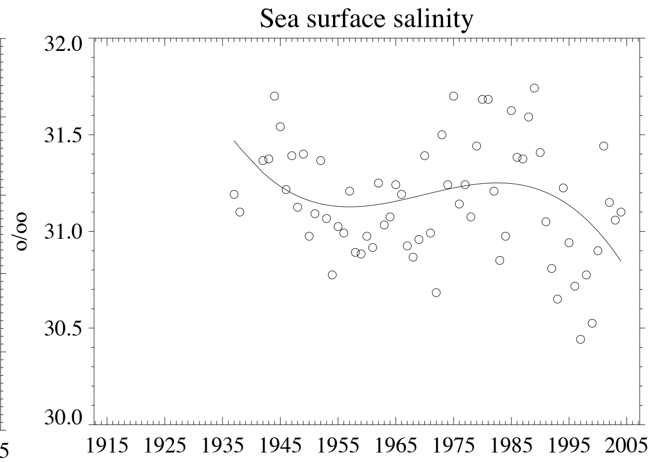

Figure 17. As in Figure 16 but for sea surface salinity, in parts per thousand.

the amount of freshwater inputs from Puget Sound Basin rivers and streams.

As with SST, SSS has only been monitored since 1990, but there are longer records from Race Rocks. The shortness of the record in the Sound precludes establishing a baseline or determining climate trends. Furthermore,, the data are taken as a single day's value and not means integrated over the month.

Nonetheless, the observed record does support some tentative conclusions about the connection between climate variability and SSS. The warmer, drier conditions of 1991-92 and fall 2000 coincided with higher SSS, whereas substantial runoff in the very wet year of 1998-99 coincided with lower SSS[69], as expected from the foregoing discussions of factors influencing salinity.

At Race Rocks (Figure 17) salinity has declined somewhat over the period of record. Freshwater input from the nearby Fraser River probably plays a substantial role; interannual variations of SSS are well correlated (r=-0.37) with regionally averaged annual precipitation estimated from Puget Sound-area stations.

It is likely that the observed changes in streamflow noted over the 2oth century have increased salinity in summer and decreased it in winter, and projected future changes in freshwater inputs will cause larger changes of salinity. Future changes in coastal upwelling rates, which are currently uncertain, would also affect future salinity levels in Puget Sound.

5.3 Density Stratification

Stratification is a major component affecting marine water quality. Density stratification refers to the horizontal layering of water in the water column by density[70]. Stratification affects mixing and circulation in marine waters, which in turn impact phytoplankton growth, the availability of dissolved oxygen and nutrients in the water column, pollutant flushing; and larvae retention[71].

Stratification in marine waters is largely affected by water temperature and salinity. Lowering the surface temperature and or raising surface salinity decrease density stratification in the water column. One study[72] found that in many areas of Puget Sound, salinity had a larger influence on density stratification than did water temperature. A major driver of the salinity differences (and, therefore, stratification) in these areas was the large amount of freshwater entering the Sound from nearby rivers, with a 50% reduc-

[69] Newton et al. 2002.

[70] Newton et al. 2002.

[71] Newton et al. 2003.

[72] Newton et al. 2002.

tion in stratification in the dry winter of 2000-2001[73]. Other factors affecting density stratification include:

- Ambient air temperature (can increase stratification if high);
- Solar radiation (can increase stratification if high);
- Surface winds (can decrease stratification through enhanced mixing);
- Internal waves (can decrease stratification through enhanced mixing); and
- Tidal circulation (can decrease stratification through enhanced mixing)[74].

Unfortunately there are no long-term records of temperature and salinity at the surface, let alone at depth, to allow estimates of previous changes in stratification of Puget Sound. The previously noted connections between climate and surface temperature and salinity imply that in summer months there will be some cancellation between increased temperature and increased salinity (because of reduced streamflow), whereas in winter months the warming and increased streamflow would increase stratification.

In the freshwater environment of the region's lakes, stratification is driven by temperature and there are indications of important changes linked to the effects of climate warming on stratification. A warming climate has apparently extended the period of summer stratification in Lake Washington from 1962 to 2002 by 25 days, mainly through earlier spring stratification (16 days). Warmer temperatures in the future may further increase the duration of summer stratification in Lake Washington.

5.4 Dissolved Oxygen

Dissolved oxygen (DO) refers to the amount of free (not chemically combined) oxygen in water. DO is an important determinant for a water body's ability to support fish or other freshwater and marine organisms. DO levels and distribution are affected by various factors, including:

- Water temperature – Increases in water temperature decrease the amount of oxygen water can hold, leaving less water available for aquatic life.
- Density stratification - Strong and/or more persistent density stratification limits the exchange of deeper, lower DO waters with more oxygen-rich surface waters[75].
- The quality of point and non-point source inflows - Point and non-point source inflows with high organic content or low DO levels can reduce DO in the receiving water body. Examples include waste discharges, agricultural discharges, and urban stormwater runoff.
- Water turbulence – Increased water turbulence can improve mixing in the water column, exposing more of the water's surface area to air.
- Upwelling - Coastal upwelling brings naturally low DO deep ocean water into Puget Sound through the Strait of Juan de Fuca. Upwelling is strongest in the late summer when winds are strongest (*ibid*).
- Organic production - DO in the lower depths of the water column can be reduced by decomposition of organic matter.

The Washington Department of Ecology uses a DO concentration of 5 mg/L as the threshold for identifying areas where biological organisms may be stressed by low DO concentrations. Waters are considered near-hypoxic, and therefore harmful to most organisms, at 3 mg/L (*ibid*). The impact of low DO levels will vary based on the organism, however.

No information on trends in DO rates in Puget Sound freshwater systems has been identified at this time. Trends in marine DO concentrations can only be evaluated since 1993 due to data limitations (*ibid*). In 1993, conductivity, temperature, and depth (CTD) casts to the seabed began. This dataset is not complete, however, since bad weather or other factors may have prevented sampling at all stations in all months (ibid). Analysis of data from 16 stations monitored since January 1993 show no clear trend in DO concentrations.

On a shorter time frame, evaluation of 50 Puget Sound stations monitored from October 1997 through December 2000 by the Department of Ecology found biologically significant low DO concentrations "relatively prevalent" in Puget Sound during this period (ibid). Of the 50 stations monitored, 28 (56%) had DO concentrations below the 5 mg/L threshold. Nineteen of these 28 stations (68%) had the low DO concentrations for more than one month in a given year.

[73] Newton et al., 2003.

[74] Newton et al. 2002.

[75] Newton et al. 2002.

Three stations (11%) had DO concentrations below the near hypoxia threshold of 3 mg/L.

No information on the impacts of climate variability on DO in Puget Sound freshwater systems has been identified at this time. Strong inter-annual variation in marine DO concentrations is evident but no formal analysis of links to climate drivers such as El Niño has been done. It is noted that a high number of low DO occurrences appear to coincide with the 1997-1998 El Niño, possibly due to suppressed coastal upwelling and reduced flushing of Puget Sound waters [76]. An anomalously high incidence of low DO concentrations in October and November 2000 may be related to the drought of 2000 although further analysis is needed (ibid). The Puget Sound Water Quality Action Team similarly noted that marine DO concentrations appeared to be lower in many areas during 2000 and 2001 than 1996 and 1997[77]. A possible reason cited by the PSWQAT is the strong upwelling and shallow thermocline associated with the 1999 La Niña (ibid), though the high precipitation and streamflow that year may be more important.

Evaluating the factors controlling DO and the likely direction of change that each might experience in a warming climate, it seems probably that DO levels at depth could decrease, increasing hypoxic conditions in bottom water. This is because increased surface populations of marine plants and animals (resulting from increased levels of productivity caused by higher water temperatures and increased winter stratification) would result in increased consumption of oxygen at depth when they die and sink.

Modeling studies should be conducted to determine the relative importance of changing climate influences (for example, changes in winds, cloudiness and freshwater inputs) versus changing nutrient inputs from septic tanks, fertilizer runoff and land use practices.

5.5 Nutrients

Nutrient inputs have important impacts on the biological and chemical processes required to support freshwater and marine species in the Puget Sound basin. Major influences on freshwater nutrient levels include point and non-point source discharges (e.g., industrial discharges, failing septic systems, stormwater runoff). Major influences on nutrient levels in marine waters include freshwater inflows from rivers and streams, density stratification (affecting the mixing of nutrients and dissolved gases in the water column), organic productivity (affecting nutrient consumption), point and non-source discharges directly into the Sound, and the nutrient content of Pacific Ocean water entering through the Strait of Juan de Fuca.

Nutrients addressed in this report include nitrogen and phosphorus. In marine waters, nitrogen and phosphorus are critical nutrients for primary productivity in marine ecosystems, particularly phytoplankton growth. Too little dissolved inorganic nitrogen can limit phytoplankton growth.

Trends analyses for Puget Sound nitrogen and phosphorus levels were conducted by the Department of Ecology for years 1991-2000[78]. The analyses examined data from 20 of 33 freshwater monitoring stations. Most stations showed no significant trend in total nitrogen or phosphorus during this time. Three of 20 stations showed declining trends in total nitrogen and five monitoring stations showed increases in total phosphorus.

Some indication of localized trends is also evident from a Department of Ecology analysis of Puget Sound's sensitivity to eutrophication. Eutrophication, which is affected by DO, stratification of the water column, and dissolved inorganic nutrient levels (e.g., nitrogen and phosphorus) [79], is a process where water bodies, receive excess nutrients that stimulate excessive plant growth (algae, periphyton attached algae, and nuisance plants or weeds). This enhanced plant growth, often called an algal bloom, reduces dissolved oxygen in the water when dead plant material decomposes and can cause other organisms to die. Using data from 1994-2000, Ecology found three of 34 stations (9%) exceptionally sensitive to eutrophication: Budd Inlet, south Hood Canal, and Penn Cove. An additional 13 stations (38%) were identified as highly sensitive.

Future nutrient levels in Puget Sound will depend to a large degree on future patterns of nutrient inputs from human sources. The overall impact of climate change on Puget Sound nutrient levels is difficult to project because of incomplete knowledge of likely competing influences. On the one hand, regional climate change is likely to increase nutrient levels overall because of sea level rise and increased leakage from septic systems. On the other hand, it may decrease winter nutrient levels because of increases in stratifica-

[76] Newton et al. 2002.

[77] PSWQAT 2002.

[78] PSWQAT 2002.

[79] PSWQAT2002.

tion. With decreased summer runoff, nutrient loading in the Sound may decrease in summer.

In any case, impacts of climate change on nutrient levels will vary throughout the year and likely from place to place in the Sound since climate change will affect the various contributing factors, such as rates of organic productivity and the timing and volumes of stormwater runoff, individually. Even the sign of the contribution of some of these changes to future nutrient levels is uncertain. Freshwater inflow to Puget Sound, for example, has the potential to both increase and decrease nutrient concentrations. First of all, it is uncertain whether increased runoff would increase or decrease nutrient delivery (the answer depends on whether increased runoff simply dilutes the nutrients previously delivered or delivers additional nutrients to the Sound). Second, even if freshwater inflow did increase nutrient delivery, because increased runoff results in increased stratification of the Sound, it causes increased depletion of nutrients by phytoplankton.

5.5.1 Fecal Coliform

Fecal coliform is used as an indicator of the presence of potentially harmful bacteria and viruses from human and animal wastes. Fecal coliform enters surface water bodies primarily through stormwater runoff, failing septic systems, livestock operations, and contaminated freshwater inputs from rivers and streams. Fecal coliform is one of three most common causes for surface water quality problems in Washington State (the others are temperature and pH)[80].

Fecal coliform is a major concern in marine waters given the potential impact of fecal coliform bacteria on commercial and recreational shellfish harvesting in Puget Sound.

A Department of Ecology analysis of fecal coliform bacteria counts at 20 freshwater monitoring stations in the Puget Sound basin showed no noticeable trend in 12 of 20 stations for the period 1991-2000. Seven stations were found to have decreasing fecal contamination counts while contamination at one station was increasing[81].

Trends in marine fecal coliform bacteria counts have been reported by the Puget Sound Ambient Monitoring Program (PSAMP) and to a lesser degree the Washington State Department of Ecology. PSAMP assessed fecal coliform bacteria trends for the five years prior to March 2001 using data collected by the Washington State Department of Health. The Department of Health intensively monitors fecal coliform bacteria using 1,114 monitoring stations in 89 shellfish growing areas throughout Puget Sound and the Strait of Juan de Fuca. The PSAMP analysis, which used a subset (302) of these 1,114 stations, found significant increases in fecal coliform contamination at 40% of the evaluated stations. Fecal coliform contamination was unchanged at 27% of the stations in this five year period while 33% of the 302 stations showed a decrease in contamination[82].

Establishing fecal coliform bacteria trends in open marine waters is more difficult given the short lifetime of fecal coliform bacteria in salt water (1-2 days) and the potential for sampling to miss runoff events known to deliver fecal coliform bacteria to marine waters[83]. Potential trends are, nevertheless, evident. Department of Ecology analysis of fecal coliform bacteria counts for 1990-2000 found one area in Puget Sound with chronically high fecal coliform bacteria counts (Commencement Bay) and three areas with sporadic but consistently high counts (Budd Inlet, Oakland Bay, Possession Sound) (ibid). Ecology also found an increasing frequency of high fecal coliform bacteria counts in summer in five Puget Sound monitoring stations since 1998 (ibid).

No specific studies have been identified to date on the relationship between fecal coliform bacteria and climate variability. However, in its analysis of marine water quality for 1998-2000, the Department of Ecology found that high fecal coliform bacteria counts often correlated with periods of high precipitation in 1998-2000[84]. In particular, Ecology noted the high precipitation periods of November 1998 through January 1999 and November 1999.

5.6 Future changes in water quality

Puget Sound water quality is strongly influenced by freshwater input (strongly a function of winter precipitation in the PNW); stream, estuarine, and coastal ocean temperatures; and pat-

[80] Beckett 2000.

[81] PSWQAT 2002.

[82] PSWQAT 2002

[83] Newton et al. 2002.

[84] Newton et al. 2002

terns of stratification and mixing between the estuary and the coastal ocean.

- Temperature: generally expect "narrowing of annual water temperature range" in estuaries (summer temperatures increase less than winter temperatures – summer temperature moderated by evaporative cooling) [85].
- Nutrient loading: in general, increased freshwater runoff would result in increased delivery of nutrients (N, P) to estuaries (ibid): in Puget Sound, with freshwater runoff increasing in winter and decreasing in summer, nutrient loading is likely to decrease in summer.
- Contaminants:
- Increased contaminant leakages from underground storage tanks/waste disposal sites as a result of sea level rise (increased soil saturation, increased corrosion of underground tanks) (location/content of such sites is largely unknown) [86]
- Increased leachates from onsite sewage systems (septic) could cause problems for Puget Sound shellfish (ibid.)
- Freshwater quality can also be affected in places by sea level rise: increased salt wedge (but perhaps ameliorated in winter by increased runoff), increased saltwater intrusion into freshwater aquifers (San Juans).

6 Marine Ecosystem Structure and Function

Puget Sound supports a stunning diversity of life within and around its waters, owing in part to the great diversity of habitat types, from shorelands and wetlands to deep marine waters to rivers and lakes. Fluctuations in climate and sea level play a role in determining the suitability of these habitats, although in considering the history of influences on these habitats, the changes wrought by humans have played a bigger role than climate in most cases.

6.1 Primary Trophic Levels

The base of the food chain includes the anchored plants, namely seaweed, seagrass, kelp, and tidal marshes; and also benthic (bottom-dwelling) microalgae and the class of tiny floating plant organisms, the phytoplankton. Major changes in these populations have been observed over the last several decades that may have resulted from changes in climate and/or human influences[87].

Major types of primary producers in Puget Sound include phytoplankton, benthic microalgae, seaweeds, kelp, seagrasses, and tidal marsh plants[88]. Important variables influenced by climate include dissolved oxygen concentration, nutrient availability, and stratification intensity, many of which are mediated through climate's influence on coastal upwelling.

In a study[89] of the nearby Strait of Georgia-Juan de Fuca estuary, the planktonic ecosystem was shown to be insensitive to variability in river inflow/estuarine mixing, but was sensitive to changes in biological rate parameters. The authors suggested that the ecosystem response to climate variability and change might occur via linkages between temperature changes and growth rates, wherein increased temperatures resulted in increased growth rates.

Thom et al. (2001) report experimental and field studies showing the controlling influence of temperature on benthic primary production, respiration, and community production. Field work suggests that benthic primary productivity is correlated with the magnitude of annual temperature range experienced at a site, decreasing with both high and low seasonal temperature ranges[90]. Changes in the amount of temperature variation "may destabilize ecosystem primary productivity as it is now developed ... For example, increased temperature ranges at marine sites may result in a shift to species that are more tolerant of wider temperature variations and vice versa."

These changes, in turn, seem to affect processes like nutrient fluxes into the water column. Increased levels of CO2 are likely to increase es-

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[85] Boesch et al. 2000.

[86] Canning 1991.

[87] Nicholls 2002.

[88] Thom et al. 2001.

[89] Li et al. 2000.

[90] Thom et al. 2001.

tuarine productivity[91]. The actual impacts of climate change on both the benthic communities and the rest of the ecosystem, however, remain highly speculative, due to uncertainty about the fine scale nature of climate changes and the complexities of ecosystem response.

In the freshwater environment of the region's lakes, there are indications of important changes linked to the effects of climate warming on stratification. A warming climate has apparently extended the period of summer stratification in Lake Washington from 1962 to 2002 by 25 days, mainly through earlier spring stratification (16 days)[92]. The spring phytoplankton bloom closely followed the spring stratification transition, whereas zooplankton species have not responded strongly, leading to a growing gap between the timing of the spring peak of phytoplankton and that of zooplankton. The bloom timing of the species *Daphnia*, which has been hypothesized to depend on daylight rather than temperature, has not changed. The shift in this previously well-timed interaction between predator and prey may have important consequences for the entire Lake Washington ecosystem if the climate continues to warm and is a good example of the subtle and complicated ways in which climate change will alter ecosystem dynamics.

6.2 Effects on shellfish and harmful algal blooms

Puget Sound is one of the largest shellfish-producing regions in the United States[93]. Puget Sound shellfish are vulnerable to contamination by the toxics produced by harmful algal bloomsoxic blooms can lead to closure of commercial and recreational shellfish beds to protect the public against paralytic shellfish poisoning (PSP), a potentially fatal illness caused by eating contaminated shellfish, and domoic acid poisoning (DAP), which can cause temporary or permanent memory loss.

Concentrations of toxins in Puget Sound shellfish and the geographical scope of shellfish closures have increased over the past four or five decades[94]. There has been a slow progression of PSP toxins from northern to southern areas of Puget Sound. Since the 1980s, the frequency of detection of PSP toxins has increased in the southern basins of Puget Sound, an area containing the region's most productive shellfish beaches. Public beaches can also be affected by these pathogens. Domoic acid poisoning has only been observed much more recently; the first closure of a Puget Sound beach due to DAP occurred at Fort Flagler (near Port Townsend) in 2003.

Growing human development of the Puget Sound region is likely a major contributor of the recent increases in PSP toxins. Increased nutrients (via activities such as aerial forest fertilizing, sewage outfalls and agricultural runoff) can provide more favorable growth conditions for the algae producing PSP toxins. Recent studies have suggested a link between climate events and the magnitude and frequency of harmful algal blooms[95]. Those algae also respond favorably to stratified conditions, while the algae that produce domoic acid are thought to be favored by well-mixed environments and warmer temperatures[96].

Climate change could increase the frequency of shellfish toxins in Puget Sound. Both increased winter stratification of water and higher water temperatures may encourage more PSP-causing algae. The ultimate magnitude and frequency of future harmful algal blooms will depend on environmental changes and human use of Puget Sound.

6.3 Nearshore Habitat

Salt marshes and eelgrass meadows (Zostera marina) are key components of nearshore estuarine habitat and food web relationships in the Puget Sound basin. These are affected by fluctuations or changes in climate via climate-induced changes in both biological and physical conditions.

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[91] Thom et al. 2001.

[92] Winder and Schindler 2004.

[93] PSAT 2003.

[94] Trainer et al. 2003.

[95] Epstein et al. 1998; Hayes et al. 2001; both cited in Trainer et al. 2003.

[96] Trainer et al. 2003.

6.3.1 Salt Marshes

Salt marshes are found near river mouths where freshwater tributaries to Puget Sound mix with salt water. Salt marshes are highly productive habitats supporting a mix of plant and animal species, including invertebrates, shrimp, crabs, salmon, terns, and herons. The plants filter suspended sediments and nutrients, regulate dissolved oxygen in the water column, stabilize bottom sediments, and baffle currents. Salt marshes also reduce flooding by retaining stormwater during high-flow periods. Salt marsh growth and distribution is affected by sea level, salinity, temperature, freshwater inputs, and tidal flooding regimes.

Studies estimate a 73% decline in Puget Sound salt marsh habitats since the mid-1800s with the most acute losses (near 100%) in heavily urbanized central Puget Sound[97]. Development, dredging/filling, erosion, pollution, and disruptions to hydrologic system (e.g., dams) have all contributed to the loss of Puget Sound salt marshes.

No information on the effects of climate variability on Puget Sound salt marshes has been identified to date. The response of tidal marshes to historical sea level rise has been examined. The accretion rate of most PNW marshes has been sufficient to keep pace with the rate of global sea level rise[98]. Marshes located in central and south Puget Sound are the most vulnerable to sea level rise, as the relative rise in those locations exceeds the global rate[99]. Anything that reduces the supply of sediments to those marshes – such as shoreline armoring or coastal development – could cause southern Puget Sound marshes to succumb to rising sea level.

Several studies have looked generally at the potential impacts of climate change on salt marshes. Assessment of specific responses to climate change is difficult due to data limitations and the lack of studies specifically looking at potential responses of sea grasses to climate change[100]. A review of relevant studies[101] found that:

- Increased water temperatures associated with climate change may affect plant distribution in salt marshes through effects on the chemical and biological processes regulating salt marshes. These include photosynthesis, transpiration, decomposition, nutrient cycling, and the accumulation of organic matter. Increased water temperatures may also affect the distribution and abundance of invertebrates. The resulting changes in the rate of herbivory and bioturbation could be detrimental to salt marshes. The types of intertidal plants found in tidal marshes may be more resilient to a warming climate, due to their ability to withstand wide temperature changes. Drying of soils, caused by warmer temperatures, could cause moisture stress[102].
- Changes in soil salinity may have positive or negative effects on salt marshes. If evaporation rates at the soil surface increase, soil salinity may increase and kill marsh plants, particularly at mid-marsh elevations. Conversely, soil salinity may be reduced if precipitation increases.
- Projected changes in precipitation are also a factor in nutrient loading and sediment accumulation. Increased precipitation could increase nitrogen levels in salt marshes through increased runoff and nonpoint source pollution, potentially enhancing productivity if nitrogen limited. Sediment accumulation may increase with more precipitation as a result of increases in freshwater runoff and erosion[103]. The additional sediment load may benefit the marsh if the rate of accumulation is consistent with sea level rise. If sediment accumulates faster or slower than sea level rise, however, changes in the biological structure and function of the marsh could occur.
- The effects of sea level rise on salt marshes will depend largely on location. In many cases, the loss of salt marsh habitat to sea level rise could be offset by the inland migration of the salt marsh. Natural bluffs, sea walls and other erosion control measures may prevent this inland migration however, effectively squeezing the salt marsh out of existence[104]. This affects not

[97] Ecology 2005

[98] Thom 1992.

[99] Thom et al. 2001

[100] Short and Neckles 1999 and Adam 2002.

[101] Short and Neckles 1999, Thom et al. 2001, Adam 2002, and Hughes 2004.

[102] Thom et al. 2001.

[103] Adam 2002.

[104] Adam 2002, Hughes 2004.

only the total acreage of available salt marsh habitat but also the type of salt marsh habitat and its primary productivity. As noted in Hughes (2004), coastal squeezing reduces the amount of nitrogen cycled through each acre of remaining salt marsh due to decreases in high marsh areas relative to low marsh. Since nitrogen levels limit primary productivity in many marine and estuary systems, any reduction in nitrogen cycling could further limit the distribution and ecological function of salt marshes.

6.3.2 Eelgrass

Eelgrass (Figure 18 - photo credit Randy Shuman, King County) is a highly productive perennial flowering plant that grows in the soft sediments of shallow subtidal zones to depths of approximately 22 feet. Eelgrass meadows provide valuable habitat and serve as a source of food for many marine species, including herring, juvenile cod and salmon, sole, flounder, shellfish, urchins, crabs, and invertebrates. Eelgrass also provides valuable erosion control along the Puget Sound coastline by softening wave and current energy. The primary growing season for eelgrass is spring and summer.

Eelgrass growth and distribution is naturally limited by light availability, substrate composition, water temperature, salinity, inorganic nutrient availability, and wave/current energy[105]. In a study focusing specifically on the effects of temperature and salinity on eelgrass, Thom et al. (2003) found that density is greatest at sites with higher salinity and lower summer temperatures. Because eelgrass is found south of the PNW, in warmer locations, it is thought to be unlikely that climate change would eliminate it from the PNW, "unless the warming occurs so rapidly as to not allow for northward expansion of these southern populations or adaptation of local populations"[106].

Human impacts have a major impact on eelgrass growth and distribution. It is estimated that 33% of Puget Sound's eelgrass beds have been lost since initially inventoried[107]. Habitat alteration related to development, including dredging, erosion control activities, and construction of shoreline structures (e.g., docks) impact eelgrass through disturbance of the substrate, increased sedimentation, and reduced light availability. Increased water temperature, excessive nutrients, invasive exotic species (e.g., cordgrass Spartina spp.), and pollution have also affected eelgrass distribution (ibid).

The influence of climate variability on eelgrass has not been extensively studied. One study focusing on factors influencing spatial and annual variability of eelgrass in coastal Washington and Oregon suggested that climate variability is likely to impact eelgrass abundance, flowering, and distribution (vertical and horizontal) in the Pacific Northwest[108]. In particular, eelgrass biomass in Willapa Bay increased in the 1998-2000 period in a manner similar to observed increases in North Pacific phytoplankton. The study also suggested a possible but untested correlation between increased flowering shoot density in Willapa Bay in 1999-2000 and the strong 1998 El Niño, a period during which low biomass and density were recorded. Finally, the study noted that the vertical depth limit of coastal eelgrass meadows might be affected on a seasonal to interannual basis by El Niño-induced increases in sea level in the North Pacific Ocean (20-40 cm above average).

Deductions about the impacts of climate change on eelgrass can be drawn from the observed connections between climate – particularly streamflow – and the factors influencing eelgrass growth. Higher winter and early spring streamflow may increase the amount of suspended solids in the water column as a result of

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[105] Thom et al. 2001, 2003.

[106] Thom et al. 2003.

[107] PSWQAT 2001.

[108] Thom et al. 2003.

increased erosion and estuarine sediment disturbance. The increase in suspended solids can reduce light availability, affecting photosynthesis in eelgrass as well as shoot density, leaf width, the number of leaves per shoot, and growth rate [109] if occurring at a time of active growth for eelgrass. Reduced freshwater runoff in summer has been observed to increase salinity [110], which may benefit eelgrass assuming salinity levels do not exceed a maximum threshold for optimal photosynthesis. Greater density in eelgrass at sites in coastal Washington and Oregon has been observed with higher summer salinity (approximately 15-33 ppt)[111]. In another study, high photosynthetic activity in eelgrass was observed at 20-35 ppt salinity[112]. Reductions in salinity below this threshold may reduce eelgrass growth and distribution. Salinity above optimal conditions force adjustments in seagrasses that can limit growth by competing for energy, carbohydrates, and nitrogen supplies. High salinity rates are also known to increase the intensity and spread of eelgrass wasting disease, which is caused by the pathogen *Labryinthula zosterae*. Salinity reduction from increased freshwater inputs may be offset to some degree, however, by increased upwelling of higher salinity waters.

Another significant factor is the temperature in the surface water layer that affects eelgrass, which has been shown to be highly correlated with air temperature to 30 meters, a depth far exceeding the maximum depth range for Puget Sound eelgrass[113]. The optimal temperature range for Puget Sound eelgrass seems to be between 5 and 8°C with stress to the plants becoming a factor around 15°C as respiration rates begin to exceed rates of photosynthesis[114]. Such temperatures are already common in south Puget Sound (Figure 19) and will become more common elsewhere in a warming climate. Root to shoot ratios, nutrient uptake, and other enzyme-controlled processes may also be sensitive to temperature increases, as might flowering and seed germination in seagrasses, although interaction with salinity may also be a factor offsetting the impacts of changes in temperature[115].

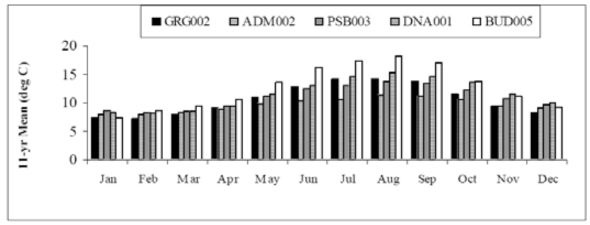

Figure 19 - Eleven year (Oct. 1989-December 2000) monthly sea surface temperature means for five Puget Sound monitoring stations: the Strait of Georgia (GRG002), Admiralty Inlet (ADM002), Puget Sound main basin off West Point (PSB003), Dan Passage (DNA001), and Budd Inlet (BUD005). Figure source: Newton et al. 2002.

Sea level rise may directly affect seagrass distribution by increasing water depth over seagrasses, reducing the amount of light available for photosynthesis at depth within the water column. It is also conceivable that sea level rise could further affect seagrass plants and habitat structure (e.g., leaf biomass, width, canopy height, pollination, larval recruitment, sedimentation rates, sediment/algal flushing) through changes in tidal circulation and flow patterns.

Increased carbon dioxide (CO2) may directly elevate the amount of dissolved inorganic carbon (DIC) in seawater. This increase may enhance seagrass distribution by improving photosynthesis and productivity – preliminary laboratory experiments with CO2 enrichment suggest that both eelgrass and bull kelp may be CO2 limited[116]. Other potentially limiting factors, including nu-

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[109] Short and Neckles 1999.

[110] Newton 1995.

[111] Thom et al. 2003

[112] Thom et al. 2001.

[113] Newton 1995

[114] Thom et al. 2003

[115] Short and Neckles 1999

[116] Thom 1996, cited by Thom et al. 2001.

trients, temperature, and light, may offset the CO_2 fertilization effect, however.

6.3.3 Future changes in nearshore habitat

Tidal marsh and estuarine habitat in Puget Sound (which have already been heavily affected by development and filling) are at particular risk to sea level rise. Sea level rise affects wetlands via inundation, erosion, and saltwater intrusion[117].

"Inundation can 'drown' existing wetlands, or can create new wetlands of existing uplands or transition zones." Coastal wetlands can survive sea level rise "if they remain at the same elevation relative to the tidal range"[118] by migrating inland. This could occur if soil accretion is rapid enough to keep pace with sea level rise (depends on rate of sedimentation within the wetland as well as the slope of the coast inland of the wetland). Survival of coastal wetlands also depends on the availability of inland real estate; wetland migration inland is often obstructed by coastal development or armoring, a situation known as "coastal squeeze," in which wetland habitat is sandwiched between coastal development and rising sea levels[119]. Without room to migrate inland, habitat in such conditions could ultimately disappear.

The topographic gradient along the coast will affect not only the ability of wetlands to migrate inland, but the areal extent and nature of the resultant wetland.

Coastal wetlands inundated by salt water once or twice a day support "low marsh" plants; areas inundated less frequently support "high marsh" species. Above the high marsh is a transition zone to upland vegetation. The transition zone may be a freshwater wetland. If the topographic gradient landward of the wetland is constant – that is, of the same topographic gradient as the wetland – then the wetland would simply shift landward with no loss of area or change in character. Topographic gradients along the coast are not ordinarily constant. Landward of coastal wetlands the topographic gradient ordinarily increases. Therefore, as sea level rises and the wetland migrates landward, the topographic zone between the mid-tide level and ordinary high water narrows, and the extent or area of the wetland decreases.[120]

In evaluating and modeling the potential effects of sea level rise on Washington state wetlands, Park et al. (1993) predict that with 50 to 200 cm sea level rise scenarios (i.e., somewhat higher than current projections), 45 to 84% of currently existing tidal flats could be lost by the year 2100, although salt marsh habitat could increase from 23 to 49% under the same scenarios if allowed to retake land currently diked and drained for pasture. If these pasture and agricultural lands were instead protected further from salt water intrusion, which would involve elaborate tide gates and pumping of marine waters, salt marsh habitat would probably suffer an overall decline as well. Rising water tables could cause a 25% increase in freshwater marsh habitat, although forested swamps could undergo minor declines. While long term wetland loss due to accelerated sea level rise will likely be minimal compared to past and current losses caused by human activities, such losses will only exacerbate past loss of habitat for diving ducks, migratory shorebirds, and shellfish, among other creatures. In some cases, however, sea level rise could actually cause the formation of new wetlands in cases where water table comes close to surface (example from Canning 1991 in the Skokomish delta).

Implications of decrease in wetlands: decreased primary and secondary productivity inputs to ecosystem, with subsequent consequences across the food web.

The areal extent of the intertidal and shallow subtidal zones, which provide important spawning habitat for smelt and Pacific herring and migration corridors for young salmon, would also be reduced by sea level rise, as a result of coastal armoring against erosion. In many cases, intertidal habitat would be lost (i.e., converted to subtidal habitat) while existing subtidal habitat would become chronically deeper until ultimate re-equilibration of sea level and erosion processes[121].

Warmer water temperatures may also negatively affect Puget Sound kelp, another important subtidal plant providing critical nearshore habitat

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[117] Canning 1991

[118] Boesch et al. 2000.

[119] Titus 1986.

[120] Canning 1991

[121] Canning 1991

and food. Both eelgrass and bull kelp ecosystems could be directly affected by higher concentrations of atmospheric carbon dioxide[122]. Laboratory experiments indicate that both species are CO2 limited – their growth increases when exposed to seawater containing higher levels of CO2.

6.4 Fish and other marine animals

Fish and other animals will be affected by climate change in many ways – directly via changes in habitat (e.g., temperature, salinity) and indirectly via changes in the availability of food.

Temperature is a dominant controlling factor of growth rates of most cold-blooded marine organisms[123]. Faster growth rates have been shown to decrease vulnerability of young organisms to predation and to increase reproductive capacity in mature organisms. Increasing water temperatures for an individual species can increase growth rates, but only to a certain point. When temperatures get too warm, not surprisingly, negative impacts occur, such as decreased growth, survival, and reproductive output and weakening of the immune system caused by this stress.

The consequences of warmer temperatures may be especially severe for species unable, at one life stage or another, to seek out cooler temperatures. Water temperatures above the optimum level for shellfish, for example, could have more severe impacts than temperatures above the optimum level for salmon that could presumably move to pockets of cooler water. Nonetheless, salmon do experience thermal barriers, as will be discussed below.

The weakened immune system that can result from the stress induced by warmer than optimal temperatures has been linked to disease epidemics in marine populations[124]. "For example, diseases affecting sea urchins have been documented under unusually warm water temperatures in both tropical and temperate waters." These changes would have cascading affects – reduced sea urchins, reduced grazing on benthic algae, etc. "The northward extension of the shellfish diseases, such as the oyster pathogens *Minchinia nelsoni* and *Perkinsus marinus*, has been linked to increases in temperature levels. It has also been postulated that epidemics in seabird populations and disease-related marine mammal strandings were also related to ENSO events and associated warm water temperatures[125].

Many migratory birds pass through Puget Sound; they will be affected by climate change impacts on food and habitat availability in Puget Sound as well as all along their route.

6.4.1 Salmon

The causes of salmon decline have been summarized as the "four H's": habitat, hydropower production, harvest, and hatcheries. Climate is an important factor in anadromous fish habitat at every stage of their lifecycle. Because of differences in life history and habitat among the different stocks and species of salmon, steelhead, and trout, the same climate events can affect different stocks and species in different ways. For example, the same ocean conditions have been good for some stocks and bad for others – according to data collected by Washington Department of Fish and Wildlife's science division, for example, marine survival rates for south Puget Sound coho have plummeted in recent years, while at the same time marine survival rates for coho in the main basin of Puget Sound and Hood Canal have been relatively high.

Still, salmon experience thermal barriers to migration when stream and estuary temperatures reach approximately 21-22ºC. At present, thermal extremes such as these are thought to be relatively uncommon in the Puget Sound, but there were numerous anecdotal reports of thermal barriers to spawning salmon migrations in the summer of 1997 for Lake Washington chinook. A study of Fraser River sockeye salmon showed that high temperatures were related to reduced growth rates[126] and have delayed upriver migration (K. Hyatt, pers. comm., 2004).

A positive change could result from warmer stream temperatures in periods (generally during the cold season) that are now cooler than is optimal for juvenile salmon and/or incubating eggs. Future coastal oceanographic conditions could conceivably change in positive ways for salmon,

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[122] PSWQAT 2002.

[123] Boesch et al. 2000; reference applies to this and the subsequent paragraph, except as otherwise noted.

[124] HEED 1998, cited in Boesch et al. 2000.

[125] Harvell et al. 1999

[126] Cox and Hinch 1997, cited in Boesch et al. 2000.

but the nature of these changes is highly uncertain.

6.4.2 Food web changes

In the north Pacific, profound changes throughout the food web have occurred, often in conjunction with changes in the climate or sea surface temperature patterns especially the Pacific Decadal Oscillation[127]. Regime changes in climate can be considered top-down, and affect not only salmon but other marine fishes, sea birds, and marine mammals across the North Pacific. Regime changes drive ecosystem changes from both the top-down, by altering physical habitat conditions (such as temperature and salinity) for top-level predators like salmon and marine mammals, and from the bottom-up, via impacts of these same changes on the . Other important changes are driven from the bottom up: a change in planktonic ecosystem.

Changes in food web in Pacific are clearly important to Puget Sound, as many higher-trophic level species occupy both environments as opportunity arises.

The complexity of interrelationships among all of the living components of the Puget Sound ecosystem prevent detailed projections of the changes that may result from the climate changes detailed here. The ultimate impacts of climate change will depend on how all of these changes reverberate across the food web as well as on the ability of the Puget Sound ecosystem to adapt to a rapidly changing chain of freshwater, estuarine, and marine conditions.

7 Research And Monitoring Needs

Many aspects of the environment of Puget Sound are changing and will change, yet there are some significant gaps in the capability of scientists and managers to measure and understand these changes. Even fairly inexpensive, simple measurements like air temperature and streamflow have been discontinued in key locations. It is vital that the stations with the longest, highest-quality records (like the stream gauges listed in Table I) be continued, in order to compare present climate with that of recorded history and determine which aspects of the environment are changing.

Probing the depths of the Sound to measure temperature, salinity, and dissolved oxygen is a far greater undertaking but equally important. The efforts of Washington's Department of Ecology to sample the waters routinely (see Figure 19, for example) are a good start and must be continued.

Concerning dissolved oxygen, especially in problematic Hood Canal, modeling studies should be conducted to determine the relative importance of changing climate influences (for example, changes in winds, cloudiness and freshwater inputs) versus changing nutrient inputs from septic tanks, fertilizer runoff and land use practices.

There is a great need for "consistent long-term monitoring data that can be used to evaluate changes in key biological populations and biologically relevant environmental variables..."[128]. For instance, although King County has made routine water quality measurements since the mid 1960s at a number of central Puget Sound locations, changes in the sampling methods prevent a quantitative analysis of this dataset for trends in water quality or other types of environmental change that might explain separately measured trends in the abundance and composition of the benthic community. "If a goal is to evaluate change in Puget Sound in the context of both natural and human influences ... it will be necessary [to] maintain a consistent, comprehensive long-term monitoring program designed to detect variations and trends in representative biotic and abiotic variables, including the normal water quality parameters as well as indicators of the plankton and fish communities. One time or annual monitoring information is only valuable when placed in this longer-term context. Without such a program, we can only continue to speculate about environmental change in Puget Sound."

In addition to monitoring of the physical properties of the environment and the species that inhabit the Sound, much research is needed to quantify the impacts of climate change on the Sound. Several sections of this report were reduced to groping in the dark, making inferences on the basis of spotty data and one or two studies with short periods of record. A basic first step would be to quantify the impacts of temperature variability, by itself, on such basic quantities as the distribution of dissolved oxygen. Since temperature is the climate variable for which future projections have the greatest reliability, this will translate into a first-order estimate of the impacts of climate change.

To enhance our ability to project how climate change would play out across an ecosystem, we need improved monitoring and modeling studies

[127] NRC 1996, Mantua et al. 1997, Francis et al. 1998, McGowan et al. 1998, Boesch et al. 2000.

[128] Nicholls 2002.

of ecosystem change. Monitoring biological conditions over time allows us to evaluate how ecosystems respond to climate fluctuations and provides us the understanding necessary to determine the likely consequences of future climate changes. While the past may not be a definitive guide to the future, this knowledge provides valuable lessons on how ecosystems function (or malfunction) when stressed. It is also important to recognize the influence of human activities on past responses to climate variation as future changes in climate will both shape and be shaped by the interaction of natural processes and human activities.

8 Conclusions

Continued human activities like the burning of fossil fuels (coal, oil, natural gas) will likely produce a globally averaged warming of 1.4-5.8°C (3-10°F) during this century[129], and warming in the Northwest is likely to be faster, roughly 0.5-1.0°F per decade.

A changing climate is likely to provoke some important environmental changes in Puget Sound, in addition to those brought about directly by the growing human population. The changes that seem likeliest are an increase in air temperature by at least 0.5°F per decade, larger in winter and spring; increases in water temperature; reductions in summer freshwater inflow to the Sound; increases in flood events; sea level rise of at least 1.6” per decade, more in south Puget Sound, with reductions in many wetland-type habitats; and changes in species composition in many ecosystems. Other important changes that may occur include an increase in winter precipitation and an increase in the intensity of precipitation, raising the risk of flooding in many rivers.

The consequences of these changes for ecosystems in and around Puget Sound cannot be determined, owing partly to the lack of studies examining the role of climate in various components of the environment and ecosystems, and partly to limitations in projecting future climate change in a region as small as Puget Sound and partly to the complexity of ecosystem response to simultaneous changes in important parameters. It seems likely, however, that important components of ecosystems will change at different rates, altering the relationships of species to each other, stressing some resident species and offering new niches to invasive species. Managing the region’s environment under such a set of unknown changes presents an important and largely unrecognized challenge[130].

[129] IPCC, 2001

[130] See Snover et al. (2005) for some strategies for managing the natural resources of Puget Sound in the face of projected climate change.

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